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THE STRENGTH OF THE EARTH'S CRUST

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PART VII. VARIATION OF STRENGTH WITH DEPTH AS SHOWN BY THE NATURE OF DEPARTURES FROM ISOSTASY

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INTRODUCTION AND SUMMARY

The first five parts of this article have concurred in showing that the crust is very strong when measured by its capacity to support great deltas, individual mountain ranges, or great internal loads due to irregularities in density not in accord with the topography. On the other hand, the altitudes of the continents as a whole, or of large sections of the continents, agree with the demands of nearly perfect isostasy. In Part VI it was shown, however, that, although even perfect isostasy threw very considerable stresses

[1] Section B, on Applications of the Theory, will be published in the following number of this *Journal*. The Introduction and Summary apply however to both sections.

upon the outer part of the crust, the maintenance or restoration of the isostatic condition through geologic time in spite of the opposing geologic activities implied the existence of an undertow below the zone of compensation. The existence of this regional isostasy for continental interiors as well as for ocean basins suggests, furthermore, that this zone of undertow is both thick and relatively very weak to resist shearing stresses. But if such a zone exists it must have important bearings on other branches of terrestrial dynamics besides that of isostasy. Its importance gives it a right to a distinct name, and it has been called here the zone of weakness—the asthenosphere. It is desirable to test its reality and its character by other lines of evidence, and such another line forms the basis of this part.

George H. Darwin has investigated the problem of the stress-differences imposed on the earth by the weights of continents and mountains. In his work the earth was assumed to possess competent elasticity throughout and the topography to be without isostatic compensation. Love has more recently treated the contrary problem of the isostatic support of continents and mountains, assuming as governing conditions that isostatic compensation was perfect within a depth of one-fiftieth of the earth's radius, 127 km., and that all shearing stresses due to topography and compensation disappeared at that depth. Below there is assumed to exist only hydrostatic pressures. In other words, Darwin postulates no isostasy and no asthenosphere; Love postulates perfect isostasy and a perfect asthenosphere. As there is known to be no truly fluid universal shell within the earth, and as isostasy for limited regions is far from perfect, the truth must lie between these two extremes. The asthenosphere must have some degree of strength and a measure of its strength is derived in this part by a study of the nature of the departures from isostasy.

For this purpose is discussed the nature of the stresses as worked out by Darwin. Then the departures from isostasy are analyzed into harmonic series. Those of long wave-length are seen to be of low amplitude, those of short wave-length of high amplitude. Now the departures from isostasy are according to their very nature without compensation and their stress effects will therefore

follow Darwin's law except in so far as the great rigidity of the outer crust will permit it to sustain loads after the manner of a continuous beam. It is shown, however, that the outer crust is inefficient as a beam, so that the results of applying Darwin's analysis will probably not be greatly modified.

It is found that the departures from isostasy are such as throw great stress-differences upon the zone of compensation, here called the lithosphere. The maximum stresses imposed by the loads found to exist within the United States lie furthermore within the outer two-thirds of that zone. The stress-differences due to this cause reach maxima probably between 3,000 and 5,000 pounds per square inch.

Within the asthenosphere, on the contrary, the stresses caused by the departures from isostasy are very small, under the United States the stress-differences at depths of from 400 to 600 km. reaching maxima probably between 500 and 600 pounds per square inch, between a sixth and tenth of those existing at higher levels.

Now the nature of those geologic actions which oppose isostasy, both the great compressive movements and the great cycles of erosion and sedimentation, are such that they tend to destroy the isostatic adjustments of whole continents and large parts of continents. By these broad actions they tend to bring larger and larger stress-differences upon the zone lying more than 200 km. deep. The limitation of their action as shown by the dominance of regional isostasy is therefore to be regarded as an effect of weakness in that zone. This then is another proof of the reality of an asthenosphere. The proof in Part VI depended upon the dynamics necessary for isostatic undertow; the proof in this part depends upon the limitations of stress with depth as measured by the existing departures from isostasy.

This is as far as the present fragmentary data and imperfect theory can safely go, but in order to visualize the arguments a curve of strength is given which shows how great a falling-off of strength there is from the upper part of the lithosphere to the middle of the asthenosphere. Below, the strength undoubtedly again increases, but the evidence for that is supplied by other lines of research than that opened by the geodetic data.

The results of this part suggest that in future investigations by mathematicians upon the elastic competence of the earth, a probable case would be to consider the isostatic compensation as uniformly tapering out through a depth twice as great as the depth given for uniformly distributed compensation, that is, tapering out through about 244–254 km. Further, it is not in accordance with nature to assume that at this depth all shearing stresses disappear. Such an assumption brings in artificialities nearly as great as those involved in Darwin's assumption of no isostatic compensation. Rather should the stress relations be solved as limited by some such curve as is here shown, and determined by the nature of the departures from isostasy. It is possible that this may add still further difficulties to the mathematical treatment of the subject, yet only by closer recognition of the realities of nature can mathematical analysis become of increasing value.

SECTION A, PRESENTATION OF THEORY

RELATIONS OF LOADS AND STRESSES

Stresses imposed by harmonic surface loads.—A harmonic series gives a succession of sweeping curves such as are shown in Fig. 15. The vertical scale may be made of any size and the curves may be regarded as sections across a series of hills and valleys, or, on progressively larger scales, anticlinoria and synclinoria, geanticlines and geosynclines, continents and ocean basins. The parts of the curves convex upward will then represent loads above the mean surface and give rise to stresses acting downward. The broad hollows give negative loads and the surface beneath is strained upward by the pressures from surrounding regions. The inequalities of the earth's surface may be taken as approximating to harmonic undulations of simple or complex nature. By so taking them, the stresses which they produce on the earth's interior may be evaluated.

G. H. Darwin treated this problem in his paper "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains."[1] In this are investigated the stresses given by positive and negative loads whose distribution follows a law

[1] *Phil. Trans. Royal Soc.*, CLXXIII (1882), 187–230.

of zonal harmonics arranged on the surface of a sphere. The harmonic series of the second order corresponds to oblateness of a spheroid and also serves as a basis for computing the tidal strains. The zonal harmonics of the fourth order correspond to an equatorial continent and two polar continents, the eighth order adds to these two annular continents in about latitude 45°, and so on. The higher orders, above thirty, correspond to a succession of anticlinoria and synclinoria, or mountains and valleys. For all above the second harmonic the depth of maximum stress lies within the outer half of the earth's radius.

Darwin's solutions were made on the assumption that there are no differences of density beneath continents and oceans and that all the relief of the earth is upheld by its rigidity. He reached the conclusion that continents such as Africa and America gave a maximum stress-difference of about four tons per square inch at a depth of about 1,100 miles. The later demonstration of the existence of regional isostasy nullifies this conclusion except for the amount by which the topography of large areas is not completely compensated. Even this part can to some extent be regarded as sustained by a rigid crust floating upon a deeper zone which acts dynamically nearly as a fluid. There are reasons for believing, however, that this latter conception is extreme in the other direction and not justified by the evidence. It is thought that by the collective support of the arguments brought out in this part the assumption will be finally justified—that for the outstanding loads not in isostatic equilibrium the work of Darwin continues to apply.

In the mathematical analysis, the loads which represent the areas and heights of the regional departures from isostasy are regarded as members of an infinite harmonic series of ridges and furrows disposed on a plane. One wave-length is the distance from crest to crest, or mid-furrow to mid-furrow. Darwin showed, as illustrated in Figs. 15 and 16, that the magnitude of the stress-difference at any point within the crust due to a surficial harmonic load depended upon the depth below the mean horizontal surface measured in terms of the wave-length and not at all on the position of the point considered with reference to the ridges and furrows. Further in regard to the direction of the stress-difference, it is

shown, as illustrated in Fig. 15, that in passing uniformly and horizontally through the crust on a line at right angles to the direction of the ridges, the stress axes revolve with a uniform angular velocity. In relation to depth, the maximum stress-difference, as shown in Figs. 15 and 16, occurs at a depth equal to $\frac{1}{2\pi}$ of the wave-length and is then equal to $2\,gwhe^{-1}$ or in gravitation units of force to $0.736wh$, in which h is the height from the mean plane to the top or bottom of the undulations and w is the weight of a unit volume.

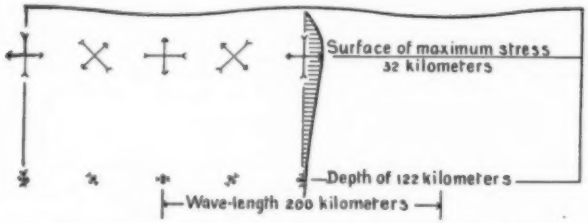

FIG. 15.—Diagram showing in vertical section uncompensated harmonic mountains and valleys with relative magnitude and direction of stress-differences, which they impose on the crust below. Mountain crests drawn as 5 km. above valley bottoms. Wave-length 200 km. Stresses shown to a depth of 122 km. Maximum stress for this wave-length is at 32 km.

It is important to note that the value of this maximum depends only on the height and density of the mountains and is independent of the distance from crest to crest. The depth at which this maximum is reached depends, on the other hand, upon the wave-length and not upon the height or density of the mountains. The effect of a doubling of the wave-length upon the vertical distribution of the stress-differences is shown in Fig. 16.

It is seen that the lateral pressure due to the elevations, instead of being at the surface as it would be under hydrostatic conditions or as in completely compensated mountains and valleys with the special distribution of density assumed by Love,[1] is at a depth of about one-sixth of the wave-length. The maximum stress is, furthermore, but 37 per cent of the full amount of the hydrostatic

[1] *Some Problems of Geodynamics* (1911), chaps. ii and iii.

lateral pressure. Fig. 16 shows that uncompensated features with a wave-length up to 200 km. impose the stresses almost wholly within the lithosphere, taking this as limited by a depth of 122 km.

The crust increases in strength to a certain maximum, perhaps from 10 to 30 km. deep, as shown by the experiments of Adams.

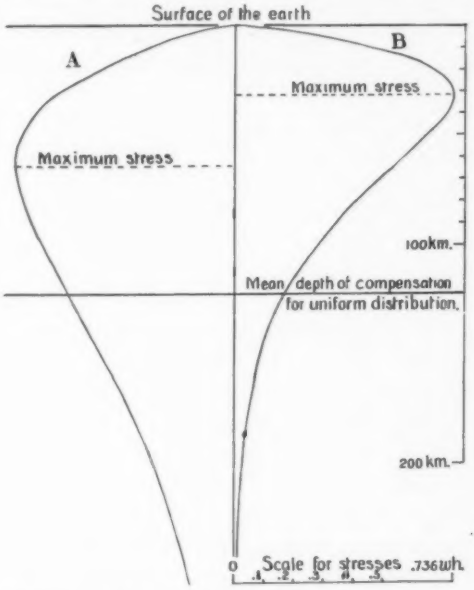

FIG. 16.—Diagram showing the distribution in the crust of stress-differences due to parallel uncompensated harmonic mountains and valleys: A, curve showing relative magnitude and depth of stress-differences corresponding to a distance of 400 km. between crests of parallel mountain ranges. B, curve showing the same for a distance of 200 km. between crests of parallel mountain ranges.

At greater depth the strength, according to the theory developed in Part VI, and as recognized by Love and others in treating of isostasy, is to be regarded as decreasing and passing by transition into the asthenosphere. Consequently it is seen that the distribution of stress imposed by a wave-length of 200 km. conforms well to the distribution of strength, the greatest strain coming on the strongest part.

Darwin obtained his results by making the initial assumption that the earth substance was incompressible but possessed elasticity of form. The introduction of the factor of compressibility Darwin showed to affect the result largely in the case of the second harmonic, but for harmonics of infinitely high orders the resulting stresses are independent of the modulus of compression. Consequently he states, "it may be concluded that except for the lower harmonic inequalities compressibility introduces but little change in our results."[1]

Modifications imposed by long and large wave-lengths.—In Fig. 16, curve A shows that for a wave-length of 400 km. the depth of maximum stress is 64 km. and at 122 km. the stress is 75 per cent of the maximum. If this should be regarded as the beginning of the asthenosphere it would mean that a large part of the stress would be thrown on to the zone incapable of sustaining large stress-differences. If the wave-length became 2,000 km. the lithosphere would be subjected to but small stress-differences and the maximum strain would occur at a depth of 320 km., the middle of the sphere of weakness. In order that Darwin's solution should hold for these cases the height of the arches would have to be so small that the resulting stress-differences would not exceed the elastic limit of the asthenosphere. For greater loads disposed on the surface in these large wave-lengths the stress relations would approach those of a rigid crust overlying a fluid substratum. Of this problem Darwin states, "The evaluation of stresses in a crust, with fluid beneath, would be tedious, but not more difficult than the present investigation" (on the stresses caused by the weight of continents and mountains).[2] It is a different problem from that solved by Love; the latter considering the stresses in such a crust caused by a condition of isostasy, not by a lack of isostasy. The limited mathematical training of the present writer does not permit here the definite solution of this problem, but some general observations can be made.

For wave-lengths very large in comparison with the depth of the lithosphere the stress-differences, if confined within the crust, approach those existing in a continuous beam, each span being

[1] *Scientific Papers*, II, 500. [2] *Ibid.*, II, 502, footnote.

stressed by a continuous load, greatest at the center in accordance with the harmonic curve and acting in the reverse direction from the adjacent spans. This is a very simple limiting case. The maximum bending moment would be on the cross-section at the crest of each downward and upward arch. For a given height of load the bending moment would increase with the square of the span or wave-length. The maximum bending stresses would be horizontal, acting as tensile and compressive stresses at the top and bottom of the lithosphere. In the middle of the lithosphere there would exist a neutral surface suffering neither tension nor compression, but subjected to horizontal shear. The theory of beams shows that the strength is limited by the marginal tensions and compressions, not by the internal shear. As the lithosphere is, however, weakest on the upper and lower margins, its material is poorly arranged to resist the bending stresses. The greatest resistance to bending in a certain plane is given by the form of an I-beam, but the crust is analogous to a beam in which a single flange should intersect its middle, giving a cross-shaped section. The earth's crust is consequently a peculiarly weak structure to resist harmonic loads of great wave-length, and as the strength varies inversely with the bending moment it varies inversely with the square of the wave-length. It is seen then that wave-lengths of continental breadth are very poorly supported by the strength of the crust, but if they reach notable amplitude must rest chiefly upon the asthenosphere. The consideration of the stress diagram given by a wave-length of 200 km. showed why very pronounced departures from isostasy can occur in one direction over areas up to at least 100 km. across and why marked regional compensation extends commonly to limits of 100–200 km. radius. The stress effects produced by harmonic loads a thousand kilometers or more in a wave-length show, on the other hand, why regional compensation of the same vertical magnitude cannot extend effectively across a whole continent. It explains why the United States as a whole is in nearly perfect isostatic equilibrium with respect to the ocean basins.

Nature of stresses imposed by internal loads.—Take the case of harmonic loads distributed on a plane *S–S*, Fig. 17, within an

indefinitely extended elastic solid. The amount and direction of the vertical stress upon this plane are shown by the vertical lines, the scale of stresses being one-twentieth of the value for the stress-diagram shown by the horizontal lines. On this plane, *S–S*, a small unit mass is subjected to stress equal in all directions and not to stress-difference, since the stress is essentially the same on the small contiguous unit masses. The reasoning is the same as

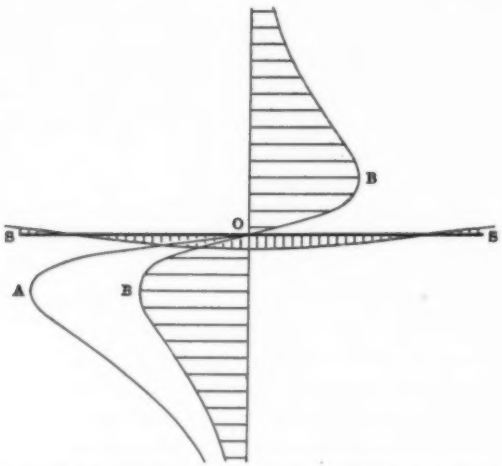

FIG. 17.—Stress-diagrams for harmonic loads distributed on a plane: A, diagram for loads upon a limiting surface of a solid extending indefinitely from this surface. B, diagram for loads upon a plane within an indefinitely extended solid. The scale for loads is one-twentieth of the scale for the resulting stresses. A little more than one-half wave-length is shown.

that for harmonic loads distributed on the limiting surface of a solid except that here there is an indefinitely extended solid on each side of the plane. The stress at any point of the plane acts positively on one side, negatively on the other. Half of the load will be carried on each side. Consequently if *OA* is the curve showing the stress-differences at various depths for a harmonic load on the surface of the earth, then *BOB* will be the stress-curve for the same load carried on a plane deep within the lithosphere. For this to be approximately true, however, the wave-length would have to be

small in comparison with the depth of the loaded surface. Then the upper half of the stress-diagram will lie within the lithosphere. The lower half of the curve would also have to lie within the elastic competence of the crust for corresponding depths. Suppose the plane to lie near to either boundary of the lithosphere. The case now approaches that of a surface load, one side of the stress-diagram becomes largely cut off and the other increases. The exact analysis is of course difficult and will not be attempted.

Assume the loaded plane to be at a depth of 61 km., half the depth of the lithosphere. The strength of the middle would not then be utilized for support of the load. For a wave-length up to 100 km. Fig. 17 shows fairly well the distribution of stress and it would be contained mostly within the middle of the lithosphere. For wave-lengths of 200 km., however, the margins of the lithosphere would be subjected to greater strain than the interior, the stress-diagram would be modified toward that existing in a loaded beam, and, if the margins are weak, the structure is poorly adapted to support the load. If the loaded plane is at greater depth, the same wave-length will throw a greater proportion of the strain upon the asthenosphere and the deeper parts of the lithosphere. If these are incapable of supporting the resulting stresses, again a modification of the diagram would occur, involving bending moments in the stronger part of the crust.

If, now, it be assumed that the upper half of the lithosphere is decidedly stronger than the lower half and that the maximum strength is at some depth below the surface, it is seen that the maximum outstanding masses which the crust could carry would be disposed in the outer quarter or third of the lithosphere. But this is just what was found to be the case as the result of the studies made in Part V. Therefore the accordance between the geodetic evidence and the consequences of the assumption raise it to the dignity of a presumption. It may be taken as a working hypothesis that the greater outstanding masses are limited in their positions by the limitations of crustal strength. Mental reservation must be made, however, as to the possibility of other more important determining factors, such for example as the nature of igneous activity, in limiting the zone of large outstanding masses. An

accordance of fact with theory is not a proof, but it raises a presumption that the theory is correct.

Nature of stresses imposed by perfect isostasy.—This topic, although not directly in line with the subject of this chapter, must receive brief mention here since the stresses in the crust are compounded of those due to the departures from isostasy with those resulting from a state of perfect isostasy. The stress resulting from the isostatic support of continents and mountains has been ably worked out by Love.[1] But his treatment started with the limiting though improbable assumption that at a depth of one-fiftieth of the earth's radius all stress-differences disappeared, as though the layer below were truly fluid. This required a complicated and equally improbable curve of density, opposite in sign above and below, in order that the topography should be compensated, the ocean surface remain a level surface, and yet the stress-differences become zero at the required depth. Nevertheless the solution is valuable as a limiting case in showing the general character of the internal stresses which must exist. He showed that isostatically compensated harmonic mountains and valleys gave maximum stress-differences on the axial lines of mountains and valleys and that it amounted to about one-fourth of the theoretical hydrostatic pressure. The stresses decrease rapidly with depth.

In contrast to Love's hypothesis of the distribution of density, that of Hayford may be considered. This is that the excess or defect in density needed for compensation is uniformly distributed to a depth of 122 km. Again, a rigorous mathematical treatment must be left to those competent to undertake it, but it would appear that such distributions of density would throw very considerable stress-differences within the asthenosphere; or, if this was incompetent to carry such, would bring large stress-differences upon the bottom of the zone of compensation, opposite in sign to that in the upper half, whereas at an intermediate level depending upon the wave-length would be a region of no stress-difference. This distribution of stress resulting from the hypothesis may be taken as a strong argument against the existence of a uniform distribution

[1] *Some Problems of Geodynamics* (1911).

to the isostatic compensation. In order to have the larger relief and its compensation fitted to a crust strongest in its upper part and shading into a zone of weakness, the zone of compensation should die out with depth and lie mostly in the upper half of the zone of strength, since the stress-differences would die out at a depth greater than the disappearance of the compensation. This conclusion is seen to be in closer accord with several other lines of evidence which have been noted than is the contrary assumption of uniform compensation.

[*To be continued*]

THE ANALCITE BASALTS OF SARDINIA

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Introduction.—In his well-known paper[1] entitled "Die Producte des Vulcans Monte Ferru," Doelter first noted the presence of "leucite basalts" at this volcano, as well as near Pozzo Maggiore, giving a brief description and an analysis. Later, Dannenberg[2] and Deprat[3] confirmed the occurrence of leucite rocks at Ferru, and showed that these flows belong to the closing period of volcanic activity. In the autumn of 1905 I visited Sardinia for the Carnegie Institution of Washington, making a special study of the different volcanoes of this island. Although my observations were necessarily brief, I was able to confirm the opinion of these geologists. The first analysis, which I made some years ago, of a specimen from Scano gave such unexpected results as regards the alkalies that I made two others of these so-called leucite rocks from other localities. All three were in harmony. Since these rocks have always been considered to be and have been cited as being leucitic, although in reality the so-called leucite is analcite, it seemed to me that a special note would be of interest. The lavas of Monte Ferru and of the other Sardinian volcanoes will be described in other papers.

I have to thank my friends, Professor J. V. Lewis for the photographs of the thin sections, and Doctors F. E. Wright and H. E. Merwin of the Geophysical Laboratory for the optical study of the analcite and biotite.

Occurrence.—Although these basalts vary somewhat in their modal characters, yet they are so closely allied that they may well be described together. One prominent locality, already noted by Doelter,[4] is a massive flow, from 6 to 10 m. thick, on the other

[1] C. Doelter, *Denks. Akad. Wiss. Wien*, XXXIX (1878), 41.

[2] A. Dannenberg, *Neu. Jahrb.*, Beil. Bd., XXI (1905), 48.

[3] G. Deprat, *C.R.*, CLV (1907), 823.

[4] C. Doelter, *op. cit.*, p. 78.

side of a small stream just north of Scano, a village on the northeastern flank of Monte Ferru. The basalt here overlies a flow of the ordinary gray trachyte of the Sennariolo type, the trachyte resting on white tuffs. Below these are tertiary marls. To the south of Scano is another flow, possibly connected with that to the north. This forms a ridge known as Binzale Prunu, which extends in a southeast direction for about 2 km. and shows three summits, called Monti Columbargiu, Martu, and Lepere. I collected lavas from the Scano flow, and from that of Binzale Prunu along the road between Scano and Cuglieri below Monte Columbargiu, and at a quarry below Monte Martu called Cava Tuvamurtas. Similar basalts were also collected at a small cone west of Bonorva, a small town east of Pozzo Maggiore, which apparently belongs to the closing phase of the last period of small cones in Sardinia. At a locality called Ghizo, to the west of Monte Urtigu, the culminating point of Monte Ferru, there is a small exposure of a similar rock containing many copper-colored biotite tables. The color of these biotite crystals makes the peasants believe that the rock is an ore of copper, and a peasant whom I met near by told me about a King Mastino, a sort of *Bergkönig*, to whom all the copper belongs. It is supposed that this king lives beneath the earth and has cast a spell upon the copper ore so that men cannot extract the copper from it.

Megascopic characters.—These lavas are all very dense, compact, and aphanitic. Apart from nodules of olivine and augite, to be described presently, the Scano flow shows few phenocrysts, a few small crystals of augite and olivine and very sparing biotites being the only ones visible. This lava is a rather darkish gray. The lava of Bonorva, which also carries olivine nodules, much resembles this except that there is no biotite. The lava flow of Binzale Prunu is almost black, quite aphanitic, though with alteration it assumes a brownish or even reddish color. In this are many tables of a bronzy biotite which are smaller but more numerous in the lava from the quarry, but larger and less numerous in that from Monte Columbargiu. The tables of this biotite are all a light chestnut brown, but when altered have a red color and a luster resembling that of copper. Dr. Merwin found that the angle

$2E = 40°–45°$ and the refractive index $\gamma_{Na} = 1.65–1.655$. These figures are high and much resemble those of some biotites of Vesuvius. There was not sufficient material to make an analysis of them. In this rock also there occurred rather abundant crystals (1–3 mm.) of a pale, greenish olivine. The rock of Ghizo is a dark brick red with many bronzy biotite tables. I was not able to obtain any fresh specimens of this, so that for the present it may be left out of consideration.

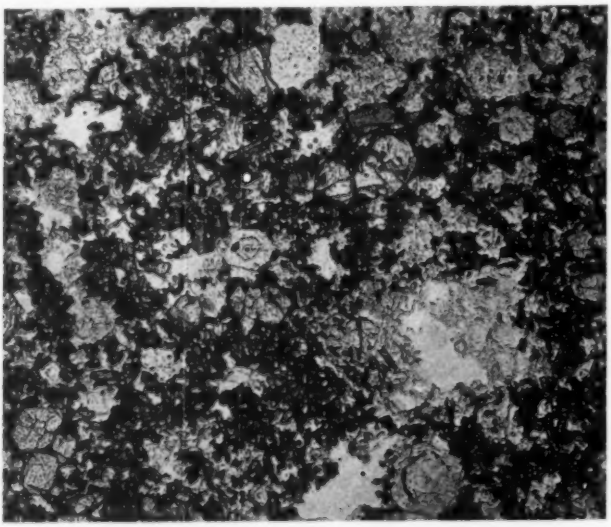

FIG. 1.—Analcite basalt, Scano

Microscopic characters (*Figs. 1 and 2*).—In all these basalts, the phenocrysts of augite and olivine are not very prominent in the thin section. The olivines vary from 0.1 to 0.5 mm. in diameter, and are generally anhedral, euhedral crystals being comparatively rare. They are colorless and quite fresh, except for a thin border of transparent bright-yellow alteration product, apparently allied to iddingsite, the amount of which is never very great. There is never any serpentinization. The augites are colorless, anhedral, smaller than the olivines, and comparatively rare. One sees scattered through

the groundmass circular areas which are clear and colorless. The diameter of these varies somewhat, in those of Scano being from 1 to 2 mm., while in that from Binzale Prunu it is never over 0.1 mm. These are almost exactly the same as the small leucites of the leucitic lavas of the Italian Peninsula. The boundaries are more or less well defined, often by a circular line of small grains. They contain the ordinary inclusions common to leucite, of augite and magnetite microlites, which form either a central core or a circular wreath.

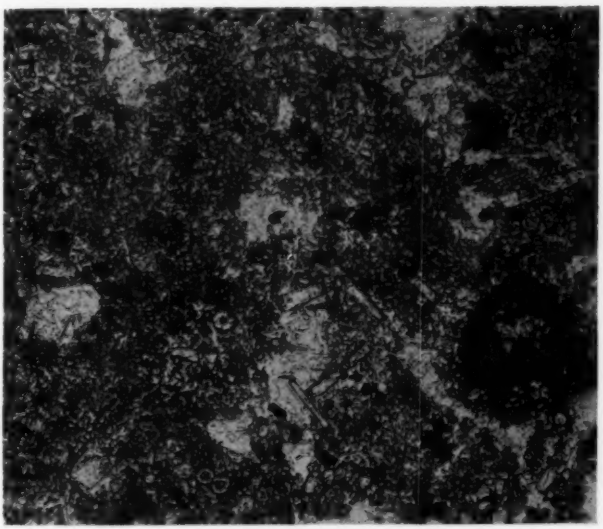

FIG. 2.—Analcite basalt, Monte Columbargiu

They are never radially arranged. All these leucite-like crystals are absolutely isotropic, even when the sensitive tint is used, and no optical anomalies or twinning phenomena are seen between crossed nicols. The observations of Dr. Wright showed that these crystals have a refractive index of 1.502, which is lower than that of leucite and above that of analcite.

The microscopic groundmass is composed of abundant, very small prisms of augite and fewer anhedral grains of olivine and magnetite, scattered without any definite arrangement in an

abundant colorless glass. Nothing was found which could be considered to be feldspar. There are some small needles of apatite.

Nodules.—The lava flow north of Scano is remarkable for the abundance of nodules of olivine and augite, which have been already partially described by Doelter.[1] Those of olivine seem to be most numerous. They are rounded, varying in size from that of a hazelnut to that of one's fist. They are composed of grains, from 1 to 2 mm. in diameter, of a transparent olivine, of a light greenish-yellow color, with a few small grains of magnetite. These grains are not very coherent, the nodules crushing down readily beneath the finger. An analysis of this olivine, extremely fresh, carefully purified and dried at 110°, gave me the results in A (Table I),

TABLE I

	A			B
SiO_2	41.24	0.687	0.689 (1.00)	43.77
TiO_2	0.10	0.001		.....
Al_2O_3	0.21	0.002		.....
Fe_2O_3	0.48	0.003		0.61
Cr_2O_3	Nil			.....
FeO	8.36	0.116	1.367 (1.99)	24.90
MnO	Trace			.....
NiO	0.21	0.003		.....
MgO	49.90	1.248		29.21
CaO	Nil			Trace
	100.62			98.49

those in B being an analysis by Doelter (*op. cit.*, p. 78). The specific gravity was 3.307 at 20°. The amount of nickel is noteworthy, as is also the entire absence of chromium, an element often occurring in olivine. There was only an unweighable trace of manganese and absolutely no lime. Leaving out of consideration the very small amounts of alumina and ferric oxide, as impurities, the ratio $RO:(Si, Ti)O_2 = 1.99; 1.00$, which is that of an orthosilicate. That of $FeO:MgO = 1:10.5$, so that the olivine is distinctly magnesian. The optical properties of this olivine will be studied later.

Doelter's analysis is clearly defective. The sum is very low and the relation $RO:SiO_2$ does not approach that of an orthosilicate.

[1] C. Doelter, *op. cit.*, p. 78.

Elsewhere[1] Doelter speaks of an olivine of Scano, of which Ippen made an analysis (not given). It is stated that the results of this correspond to the composition $7(Mg_2SiO_4) \cdot 3(Ca_2SiO_4)$. This would be a most extraordinary olivine, unique in mineralogy, and almost corresponding to a monticellite, although occurring in an igneous rock. But unfortunately the analysis has never been published, and one does not even find it in the elaborate *Handbuch der Mineralchemie* of Doelter, either under monticellite or under olivine. Regarding this olivine, Professor Doelter has been kind enough to write me (December 31, 1907) that it is white, forming isolated grains, and not in granular nodules like the olivine described above. He says that its locality is near Scano, that it is very rare, and that it has nothing in common with the olivine of the nodules.

The nodules of augite are subangular and smaller than the others, from 1 to 5 cm. in diameter. They are very compact, not granular, each one made up of a single crystal of the pyroxene, often twinned, and more or less split up through cleavage. The pyroxine is greenish-black, and it seems to be free from inclusions. An analysis gave me the following results:

SiO_2	50.13	NiO	0.02
TiO_2	1.91	MgO	13.73
Al_2O_3	7.08	CaO	20.06
Fe_2O_3	1.10	Na_2O	1.88
FeO	4.41	K_2O	0.25
MnO	0.05	H_2O	0.11
			100.73

Its chemical composition will be discussed later, when its optical properties shall have been studied.

Chemical composition.—Analyses made by me of three of these basalts are here given (Table II), along with several others of related rocks.

The three analyses of Sardinian basalts resemble each other quite closely in their general features. As regards most of the constituents, they are not specially noteworthy. Silica is rather low for basalts, and titanium is high, the latter a feature common

[1] C. Doelter, *Phy. Chem. Miner.* (1905), 64.

to the rocks of Sardinia, as has been already pointed out.[1] The presence of a noteworthy amount of nickel is also of interest. The most striking feature—when the presence of "leucite" is considered—is the small amount of alkalies and the dominance of soda over potash. The presence in all three of from $2\frac{1}{2}$ to 4 per cent of water, in spite of the evident freshness of the rocks, is also noteworthy.

TABLE II

	A	B	C	D	E	F	G
SiO_2	44.85	44.37	46.54	45.59	44.16	40.81	42.30
Al_2O_3	12.55	11.36	12.68	12.98	12.96	13.08	18.22
Fe_2O_3	3.33	7.23	3.41	4.97	8.07	6.40	17.30
FeO	5.30	3.49	5.29	4.70	3.10	7.20	.....
MgO	10.27	9.28	10.09	8.36	10.83	10.03	6.66
CaO	8.32	8.50	8.00	11.09	12.26	10.12	11.01
Na_2O	4.77	3.67	5.11	4.53	1.32	2.43	1.31
K_2O	0.72	0.74	1.64	1.04	0.72	0.31	2.93
H_2O+	2.01	3.28	2.35	3.40	2.41	3.97	0.55
H_2O-	0.95	1.95	0.25	0.51	0.46	0.82	.....
TiO_2	5.07	5.21	3.98	1.32	2.06	3.86	.....
ZrO_2	.....	.....	.....	0.03	.....	.....	.....
P_2O_5	1.17	0.99	0.91	0.91	1.03	0.88	Trace
Cl	.....	.....	.....	0.05	.....	.....	.....
MnO	0.07	.....	.....	0.14	.....	0.07	Trace
NiO	0.23	.....	.....	.....	.....	.....	.....
BaO	.....	.....	.....	0.13	.....	.....	.....
SrO	.....	.....	.....	0.12	.....	.....	.....
	99.60	100.07	100.25	99.87	99.98	99.98	100.28

A. Analcite basalt [III. (5) 6. 2. 5]. Scano, Monte Ferru, Sardinia. H. S. Washington, analyst.

B. Analcite basalt [III. 5. (2) 3. (4) 5]. Monte Columbargiu, Monte Ferru. H. S. Washington, analyst.

C. Analcite basalt [III. 6. 1 (2). 4]. Bonorva, Sardinia. H. S. Washington, analyst.

D. Analcite basalt [III. 6. 2′ 4 (5)]. The Basin, Cripple Creek, Colorado. Hillebrand, analyst. Cross, *Jour. Geol.*, V (1897), 689.

E. Leucite basalt [III. 5. 4. 4]. Dobernberg, near Tetschen, Bohemia. R. Pfohl, analyst. J. E. Hibsch, *T.M.P.M.*, XV (1896), 255.

F. Analcite basalt [III. 5.″ 4.″ 5]. Rathjordan, County Limerick, Ireland. G. T. Prior, analyst. G. T. Prior, *Min. Mag.*, XV (1910), 317.

G. Leucite basalt. Scano, Monte Ferru, Sardinia. C. Doelter, analyst. C. Doelter, *Denks. Akad., Wiss. Wien*, XXXIX (1878), 80.

Doelter's analysis (G) of the Scano rock is obviously at fault in several particulars. The alumina is much too high because of the non-separation of TiO_2 and P_2O_5, and probably also in part through the incomplete separation of MgO from Al_2O_3, as his MgO is much

[1] H. S. Washington, *Q.J.G.S.*, LXIII (1907), 69.

lower than that of any of the three rocks analyzed by me. His Fe_2O_3 is also undoubtedly too high (apart from the non-determination of FeO), presumably because zinc was used for the reduction preparatory to titration with permanganate, part of the TiO_2 being thus reduced and estimated as Fe_2O_3. His alkalies are also low, and it seems possible that they have been interchanged. This analysis may therefore be left entirely out of consideration. Dannenberg (*op. cit.*, p. 50) gives the silica percentage of the Scano rock as 44.16, which agrees very well with my results, especially as a little silica would be recovered from the alumina precipitate.

Occurrence of analcite.—The results of these analyses render it highly improbable that the leucitic mineral is really leucite, and indicate clearly that it is analcite. To test this, the alkalies were determined in the portion of the Scano rock soluble in warm dilute hydrochloric acid. This gave $Na_2O=2.66$ and $K_2O=0.12$ in percentages of the rock; that is, more than half the soda and about one-sixth of the potash. Some of this soda is probably derived from the glass base, but its amount is so great, and that of potash so small, that it leaves no doubt that the rounded isotropic crystals are analcite. The entire absence of twinning lamellae and optical anomalies is also in harmony with this supposition, as it is well known that analcite, especially when not freely crystallized in cavities, is much less prone to show such phenomena than is leucite.[1]

The very fresh condition of the rocks analyzed precludes the idea that the analcite is secondary and replaces an original leucite—a supposition which is often invoked apparently only because of a disbelief that a hydrated, zeolitic mineral like analcite can be primary. The occurrence of primary analcite has been shown by several petrographers,[2] and there is also considerable experimental evidence, which cannot be gone into here, that confirms the view that such a primary character is not only quite possible, but very

[1] The absence of cleavage does not militate against the idea here advanced, as it is not a strongly marked characteristic of small analcites in thin section.

[2] W. Lindgren, *Proc. Cal. Acad. Sci.*, III (1890), 51; L. V. Pirsson, *Jour. Geol.*, IV (1896), 686, and *U.S.G.S., Bull. 237* (1905), 154; W. Cross, *Jour. Geol.*, V (1897), 684; J. W. Evans, *Q.J.G.S.*, LVII (1901), 38; G. W. Card, *Rec. G.S.N.S.W.*, VII (1902), 100; A. Lacroix, *Mater. Min. Mad.*, I (1902), 197.

probable in many cases. Indeed, in view of the experimental formation of analcite at temperatures of 500° and higher, the known presence of water in rock magmas, and the great lowering of the melting-point through its presence, the primary character of the analcite is the only rational view in such cases as these and many others, where the rock is unquestionably fresh and unaltered. Such an explanation is far simpler and more intelligible than the invocation of the entire, or almost entire, replacement of potash by soda in a single mineral of the rock through assumed soda-bearing solutions of quite hypothetical origin, with no alteration of the other minerals. At the same time, of course, there is no question that in some cases, where the rock has undergone alteration, the analcite present is secondary, as it is in that from Rathjordan.

It may be mentioned that the occurrence of primary analcite in monchiquites and analcite basalts and other such rocks has a bearing decidedly adverse to Brun's hypothesis that lavas are water-free, as does also the fact, well known to all petrographers, that many unquestionably fresh and recent pitchstones and other glassy rocks carry up to 10 per cent of H_2O.

With my three analyses are given others of closely similar rocks, which likewise contain small, rounded crystals of a mineral which looks like leucite and which in all cases is entirely isotropic and without twinning. Indeed, those from Colorado and Ireland were considered to be leucite basalts until chemical analysis showed the true character of the isotropic minerals. These two carry no biotite. In the case of the Bohemian rock, which, like those of Binzale Prunu, contains large plates of biotite, Hibsch apparently overlooked the significance of the dominance of soda over potash. This has been pointed out by Prior in the paper cited. Chemically, they are much like the Sardinian lavas, but are higher in CaO and also in TiO_2. The last two are also much lower in soda.

Classification.—The norms of the three Sardinian basalts analyzed by me are given in Table III. From this it appears that the Scano rock (A) falls in the subrang represented by the symbol III. (5) 6. 2. 5, there being just sufficient normative nephelite present to be taken into consideration. This subrang is as yet only represented by the Scano rock and a basalt glass from the Val di Noto,

Sicily,[1] and the name of *scanose* has been given to it by me.[2] The Columbargiu rock falls in the subrang ornose, with the symbol III. 5. (2) 3. (4) 5. The Bonorva rock has the symbol III. 6. 1 (2). 4. This subrang, III. 6. 1. 4, has been called pienarose by Brouwer,[3] but a recalculation of his analysis shows that the pienarite (aegirite phonolite) described by him is really in III. 5. 1. 4. The name pienarose should therefore be applied to this subrang (III. 5. 1. 4), and the name pilandose may be given to III. 6. 1. 4, in which falls a Pilandsberg lujavrite described by him.[4]

TABLE III

NORMS OF ANALCITE BASALTS OF SARDINIA

	A	B	C
Or	4.45	4.45	15.59
Ab	28.30	31.44	15.98
An	10.56	11.95	3.61
Ne	6.53	.....	14.62
Di	17.93	15.12	23.79
Hy	.....	5.00	.....
Ol	12.18	7.84	10.21
Mt	2.32	.....	4.87
Il	9.73	9.45	7.60
Hm	1.76	7.23	.....
Pf	.....	2.18	.....
Ap	2.69	2.35	2.02

Mode.—Owing to the very fine grain, the confused fabric, and the presence of abundant glass, it is impracticable to determine the mode by Rosiwal's method, and calculation of the mode by readjustment of the norms is also subject to some uncertainty through the presence of analcite. An attempt has, however, been made to determine the modes by comparison of the several norms with the respective thin sections, and checked by a Rosiwal measurement of the analcite areas. The results are given in Table IV, but they are to be regarded as only rough approximations.

[1] G. Pontes, *Atti Ac. Gioen.* (5), III, No. X (1910), 7.

[2] H. S. Washington, *C.R. XII Cong. G. Int.*, 1913.

[3] H. A. Brouwer, *Transv. Nefel. syen.* (1910), 50.

[4] *Ibid.*, p. 132. This course has been decided on in conference with Drs. Cross and Iddings.

These three are all similar in their general features. In C, it is evident that some of the normative olivine has gone into the biotite. It may be added that the small amount of excess TiO_2 (represented normatively as perofskite) has been assigned to biotite, the somewhat abnormal composition of which is indicated by its optical characters. The large amount of glass is very striking, as well as the general composition which must have been assigned to it in each case had it crystallized. For A and B, it would have about the composition Ab_1An_1, including a little orthoclase with a small amount of analcite. In C, the 40 per cent would be distributed approximately as follows: orthoclase, 15; andesine (Ab_2An_1), 20; analcite, 5. While the figures given here and in the table are admittedly only rough approximations, yet there can be no doubt that they give an idea of the general order of the various minerals present.

TABLE IV

	A	B	C
Analcite	8	5	10
Augite	20	20	25
Olivine	12	6	10
Biotite	.....	5	.....
Ores	15	18	13
Apatite	3	2	2
Glass	42	44	40

A. Mode of analcite basalt. Scano.
B. Mode of biotite-analcite basalt. Monte Columbargiu.
C. Mode of analcite basalt. Bonorva.

Rock name.—The name of analcite basalt, first proposed by Lindgren,[1] is entirely applicable to these rocks, and is preferable to that of monchiquite, which was originally applied to rocks in which the analcite is present in the base or as a glass of the same composition. It is worthy of remark that, had the rock solidified under such conditions as to be holocrystalline, the modes given above show that a very considerable amount of andesine or labradorite would have been present (as has been the case in the Bohemian rock cited above). In this case, the name analcite basanite would have been appropriate.

[1] W. Lindgren, *Proc. Cal. Acad. Sci.*, III (1890), 51.

The presence of considerable biotite in the rocks of Binzale Prunu and Ghizo is so striking that they may be considered to form a special type of analcite basalt, which may be called ghizite, if a special name be deemed advisable.

The occurrence of analcite in these rocks, as well as in those of Colorado, Ireland, and elsewhere, which, without chemical analysis, can only with great difficulty be distinguished from leucite, so that the rocks are on superficial examination considered to be leucite-bearing, indicates the necessity of chemical analysis, and the advisability of a revision of some of the occurrences of so-called leucitic rocks. This is especially true of certain regions, such as Bohemia, Kula,[1] and Trebizond, where basalts containing a mineral supposed to be leucite occur, but where the rocks and the regional magmas are eminently sodic rather than potassic. As a general rule, as is well known, analcite is apt to occur in the rock base as the last, or one of the last, products of crystallization, but its undoubted occurrence in the instance described in this paper and those occurrences cited in the table of analyses show that its presence in leucite-like phenocrysts may be much more general than has been hitherto supposed, and may clear up some of the obscurities surrounding the occurrence of leucite.[2]

[1] It now seems highly probable, in view of the present study, that the supposed leucites of the "leucite" kulaites of Kula are in reality analcites. Though the potash is higher than in the rocks cited above, yet they are dominantly sodic, and the supposed leucites rarely show optical anomalies.

[2] Cf. H. S. Washington, *Jour. Geol.*, XV (1907), 277.

ON THE CONDITIONS UNDER WHICH THE VEGETABLE MATTER OF THE ILLINOIS COAL BEDS ACCUMULATED

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All students of the subject agree that coal was derived from vegetable material which has undergone imperfect decomposition without free access of air. The complete explanation of the coal beds involves, among other things, an explanation of (1) the method and conditions under which the plant material accumulated; (2) the kinds and proportions of the different plants that contributed the vegetable material; and (3) the chemical changes by which the plant tissues were transformed into coal. The first part of the problem, with regard to the method and the conditions under which the vegetable matter of the coal beds accumulated, can be studied somewhat independently of the other two, and the solution should be found in the structural features of the coal beds and associated strata.

Two important theories have been proposed to explain the mode of accumulation of the vegetable matter of coal beds. The older of these, known as the "transport or driftage theory," assumes that the vegetable materials grew on land areas, whence they were carried by streams and deposited in the bodies of water where they accumulated. The other, known as the "swamp or growth-in-place theory," was suggested in 1778, and assumes that the vegetable matter of coal beds accumulated in swamps practically in the places where the plants grew.

The following facts presented in the principal coal beds of Illinois make impossible the application of any form of the transport theory of accumulation of the vegetable material: (1) the great extent of the coals—the Herrin (No. 6) and Springfield (No. 5) beds extend in practical continuity over at least 7,000 square miles, and probably over a considerably greater area in the state; (2) the

regularity of thickness of the coals—the Herrin (No. 6) bed ranges from 7 to 9 feet over a known area of at least 5,000 square miles. A thin band of shale or shaly coal ("blue band"), one-half to two inches thick, is present 18–24 inches above the floor of this coal over practically the entire area of its distribution, and the thickness of the benches above and below the "blue band" is remarkably uniform. The Springfield (No. 5) bed, also, scarcely varies one foot in thickness over more than 5,000 square miles; (3) the small percentage of mineral matter or ash in the coal shows that very little mud and sand sediments were mixed with the plant remains as they accumulated.

In times of flood the amount of mud and sand carried by streams is so great compared with the amount of vegetable matter, and the latter is deposited so irregularly, that it can scarcely be imagined how the plant material of these coal beds could have been carried by streams into the Illinois basin, and have accumulated in practical continuity over such extensive areas, in anything like such uniform thickness, and with so little mingling of mineral sediments. Extensive areas of relatively pure vegetable matter are known to be accumulating in swamps at the present time, but there is no known place where plant remains transported by streams during floods are accumulating as a continuous bed over any considerable area in anything approaching regularity of thickness and without a very large mixture of sand and mud; nor does it seem probable that pure transported vegetable deposits have ever accumulated over any considerable area in the past.

From a study of the small coal basins of France in recent years Fayol, supported by De Lapparent and other French geologists, has revived the transport theory of accumulation of the vegetable matter of coal beds. However, practically every geologist who has studied extensive coal beds, especially those of the Appalachian region of the United States, with which the coal beds of Illinois are comparable, has rejected the transport theory of accumulation as applied to those beds. Rogers Brothers, Lesquereux, Dawson, Andrews, Dana, Orton, Stevenson, White, and Ashley have all accepted the growth-in-place theory of accumulation of the vegetable matter of extensive coal beds as the only one that is consistent

with the facts. It seems safe to assume, then, that the vegetable matter of the coal beds of Illinois accumulated practically in the places where the plants grew.

The acceptance of the growth-in-place theory of accumulation does not settle the question whether the basins bordered the sea, as lagoons, or occupied broad depressions over coastal plains, as the Dismal Swamp, or covered large areas over river flood plains; nor is it purposed to discuss this phase of the question at this time. The fact that the vegetable matter of coal beds accumulated under water in the places where the plants grew does not prove that the water was ever more than a few inches, or at most a very few feet, in depth, even where coal beds 5–10 feet thick have been formed. On the contrary, the structural features of the coal beds indicate conclusively that the water in which the vegetable matter accumulated was very shallow as well as that it was very quiet.

STRUCTURAL FEATURES OF THE COAL BEDS

One of the more conspicuous structural features of the coal beds of Illinois, which are representative of the larger beds everywhere, is their stratification, the more prominent bedding planes being 3–5 or more inches apart. These bedding planes form partings along which the coal separates rather easily, and they usually show well-developed bands of "mother coal" or mineral charcoal. These stratification planes often become more conspicuous when the bed is weathered, but some of them are prominent on unweathered faces. Such a conspicuous clean parting of mineral charcoal occurs 20–24 inches below the roof of the Herrin coal over several hundred square miles in western and southern Illinois, and appears to be almost coextensive with that bed. Along this charcoal zone the coal separates so perfectly that where the overlying shale does not stand well in the mines the bench above this parting is left for a roof. Five or six inches higher is another mineral charcoal parting almost equally well developed and persistent.

Between the more prominent partings and bedding planes the coal from roof to floor is made up of alternating bright and dull laminae, which are usually $\frac{1}{2}$ to $\frac{1}{32}$ of an inch thick, though in places they are considerably thicker. The aggregate dull bands generally

make up nearly or quite one-half of the coal beds, and they appear to be of the same general nature as the bedding planes mentioned above. They are often rather uniform in thickness over considerable areas, but in places they thicken for some distance and in others they thin down to knife-edge partings. The bright laminae appear to be rather homogeneous in structure; but where the coal is split along well-developed dull laminae the cleavage planes almost always show distinct mineral charcoal surfaces. A typical dull lamina appears to be composed of a film of dull, structureless coal at the top, which passes downward into coarse-textured, fibrous, mineral charcoal in the middle part, and this, in turn, grades downward into a film of dull, structureless coal below.

The features above described are not peculiar to Illinois coals. H. S. Rogers and others have noted the alternations of laminae of bright and dull coal, and the predominance of mineral charcoal in the dull laminae, in the coals of the Appalachian region, and the writer has observed the same characteristics in the coals of Iowa. They have been described from coal beds generally in different parts of the world. The mineral charcoal is so constantly present, and so intimately mingled in, and constitutes such an important part of, the dull laminae of the coals of Illinois that they must have been developed together, and a satisfactory explanation of the one must also explain the other.

THE "MOTHER COAL" OR MINERAL CHARCOAL

Two main explanations have been proposed to account for the origin of mineral charcoal. One of these, held by many paleobotanists and chemists in recent times, explains the mineral charcoal as formed from charred plant tissues resulting from forest fires sweeping over land areas, the charred fragments being subsequently swept by flooded streams into the basins, where they were deposited with the mass of vegetable matter there in process of accumulation.

This explanation assumes that a considerable part of the vegetable matter of the coal was transported material, which assumption is open to all of the objections to the transport theory mentioned above. It assumes that a very important proportion of the coal

was derived from plant tissues that had been charred by fires previous to their accumulation, and that these charred fragments had been carried into the coal basin by streams in such enormous quantities as to cover the surface of practically the entire area of the present coal beds, 5,000–8,000 square miles or more in extent; that this process took place not only once but was repeated as many times as there are persistent dull, charcoal-bearing laminae, requiring scores of recurrences of such charcoal deposition during the accumulation of the vegetable matter of each of the large coal beds. It assumes such a depth of water above the accumulating vegetable matter that the charred fragments brought in by the streams could be freely floated out above the mass of vegetable matter already present to every part of the basin, and, most impossible of all, that the streams that carried such vast quantities of charred vegetable matter carried little or no mud or mineral sediments. If it is assumed that the water of the basin was so shallow that the clay and sand brought down by the streams were strained out in the meshes of the tangled plant débris at the margin, then the same vegetable sieve would catch the charred plant fragments and not permit them to be distributed to every part of the accumulating coal beds. This explanation is not in harmony with the facts of the vertical and horizontal distribution of the mineral charcoal bands in the coal beds.

The modification of this view assumes that the mineral charcoal represents partially burned vegetable matter resulting from fires sweeping over the surface of the marshes in which the vegetable matter of the coal beds was accumulating. It is not probable that fires started by lightning would travel over water-covered swamps with only the living undergrowth and green leaves and branches of the trees to support the flames, and if they did, they would not leave such uniform and thick layers of charcoal as occur in well-developed dull laminae. If it is assumed that the surface of the vegetable matter that had accumulated in the swamp had been exposed and dried before the fires swept over it, then the conditions involved would be similar to those under which the charcoal is interpreted as having been formed by the partial atmospheric decay of the upper surface of the

vegetable material of the bog exposed during periods of unusual low water.

It seems to the writer that the explanation of mineral charcoal as resulting from the temporary exposure and partial atmospheric decay of the surface portion of the vegetable matter in the bog, instead of the assumption that it must have been charred by fire, is much more consistent with the following facts: (1) the frequent repetitions of the dull laminae containing such large amounts of mineral charcoal; (2) the larger number of plant spores in the dull laminae than in the bright coal; (3) the numerous pinnae and pinnules of ferns[1] in the midst of the mineral charcoal fragments; (4) the absence of layers of ash that would result from the burning of the vegetable matter at the surface of the bog; and (5) the changes that take place in the vegetable matter at the surface of shallow marshes during periods of drought and exposure at the present time.

EXPLANATION OF THE BRIGHT AND DULL LAMINAE

In explaining the origin of the bright and dull laminae, Dawson[2] maintained that it is the outer bark of flattened tree trunks that alone formed the shining coal. In a recent paper on the origin of bright laminae of coal, Pringle,[3] of the Geological Survey of Great Britain, reaffirms Dawson's view.

The serious objection to this view is the fact that the bright and dull laminae of the coal beds are so nearly parallel and are often continuous for long distances. Trees that are overturned in swamps fall in various directions, and their trunks lie across one another at different angles. If the cortical portion of tree trunks formed the bright laminae of coal, these bright laminae would not be continuous for long distances, and the dull laminae would be broken at short intervals by small areas of bright coal representing the cross-sections and oblique sections of the cortical

[1] David White, *Econ. Geol.*, III (1908), 302.

[2] J. W. Dawson, "On the Conditions of the Deposition of Coal," *Quar. Jour. Geol. Soc.*, XXII (1866), 141.

[3] John Pringle, "On the Origin of Bright Laminae of Coal," *Trans. Edin. Geol. Soc.*, X, Pt. 1 (1912), 33.

portions of tree trunks that lay at different angles and at different levels from those that formed the bright bands in any exposure. The distribution of the bright and dull laminae is not consistent with this explanation.

Microscopic examination of bituminous coal has shown that spores are more numerous in the dull laminae than in the bright, and hence some geologists have concluded that the dull laminae resulted from the greater number of spores in these bands, while the bright laminae were formed from the more woody portions of the plants. However, a study of the dull laminae shows that, while they may contain spores in greater abundance than the bright laminae, yet they are very largely composed of mineral charcoal, which certainly has been derived from plant tissues other than spores.

The alternation and great extent of the bright and dull laminae are such constant features of the coal beds, and the mineral charcoal is so generally present in the dull laminae, that any adequate explanation of the origin of these features must involve agencies that were repeatedly operative over practically the entire area of accumulation of the coal beds. The only recurrent agency of such widespread action is change in the water level of the basin during the time the vegetable material was accumulating.

If it is assumed that the dull laminae resulted from the flooding of the basin, we should have associated with the dull laminae bands of mud deposited during such times of flood. We are not left to speculate with regard to the effects of flooding of the basin during the progress of accumulation of the vegetable matter of the coal, for we have such an example in the clay band or "blue band" of the Herrin (No. 6) coal, which extends over practically the entire area of its distribution, and is clearly a mud parting due to flooding. Black shale partings, common in portions of some coal beds, as in coal No. 1, are also records of flooding of the coal-forming marshes. The typical dull laminae and mineral-charcoal zones in the large coal beds of Illinois, as elsewhere, are not such mud partings. They usually contain only a slightly, if any, greater percentage of ash than the bright bands and are practically free from clay silt. They contain a relatively smaller percentage of volatile matter and a

larger proportion of fixed carbon than the bright bands. A number of proximate analyses of mineral charcoal compared with those of average coals from the same beds are given in Table I. It will be seen from this table of analyses that the mineral charcoal generally contains but little, if any, more ash than the average coal of the bed in which it occurs.

TABLE I

PROXIMATE ANALYSES OF MINERAL CHARCOAL AND AVERAGE COALS FROM THE SAME SEAMS

(*a*) Charcoal Samples; (*b*) Average Samples

	Water	Volatile Matter	Fixed Carbon	Ash	Ash in Charcoal above or below That in Average Sample
1*a*	1.17	19.77	72.13	6.93	+4.69
1*b*	1.94	39.26	55.83	2.24	
2*a*	.75	20.36	71.07	7.82	+3.04
2*b*	1.37	37.80	54.46	4.78	
3*a*	2.39	12.40	75.34	9.87	+4.20
3*b*	1.68	34.97	57.00	5.67	
4*a*	.52	14.32	64.03	21.13	+3.92
4*b*	1.04	28.01	49.24	17.21	
5*a*	.55	9.92	81.37	8.16	−1.97
5*b*	.85	16.85	69.58	10.13	
6*a*	.85	88.36	87.64	3.15	−2.18
6*b*	1.19	20.76	71.70	5.33	
7*a*	.57	20.98	70.37	8.08	−2.52
7*b*	.77	17.11	70.74	10.60	
8*a*	.85	10.49	84.01	4.65	−3.74
8*b*	.94	17.85	72.15	8.39	
9*a*	1.58	23.96	64.28	10.18	− .54
9*b*	2.33	34.91	52.03	10.72	

Nos. 1–8, analyses by McCreath, *Second Geological Survey of Pennsylvania*, Vol. MM, pp. 1–107; moisture at 225 degrees F.

No. 9, analyses Illinois Geological Survey, Herrin (No. 6) coal, Williamson County, Illinois; moisture air-dried.

After discussing the original amount and the composition of the ash contained in living species of such types of coal plants as lycopods, ferns, and equiseta, Stevenson[1] concludes that "one should expect to find in ordinary [pure] coal not much less than 6 per cent of ash, or even more, in which silica and alumina should predominate greatly." He thinks it probable that coals containing less inorganic matter than the plant substance should have yielded have

[1] J. J. Stevenson, "The Formation of Coal Beds," *Proc. Am. Phil. Soc.*, LII (1913), 107.

had some of the original inorganic content removed in solution. It is also probable that some coals which locally contain more than the original amount of inorganic content, as pyrites lenses, etc., have been situated in places favorable for deposition of minerals rather than solution, and in this way have become enriched in their mineral content. It is also probable that in many places a small percentage of the inorganic constituents of the coal, above that originally present in the plants, may have come from wind-blown dust that settled over the coal basin during the long period of accumulation of the vegetable matter. The amount of ash in a coal bed varies very considerably at different levels and in different places even in the same mine. Among the possible causes of such variation are differences in the proportions of the kinds of plants that formed the coal, removal and deposition of mineral matter by solutions, and wind-blown dust. Hence, in the absence of definite evidence of sediment contributed by water, such as black shale or mud partings, it is thought that, as far as the bearing on the conditions of accumulation of the vegetable matter is concerned, not much significance can be attached to the variation in the amount of ash in a coal bed of a small percentage above or below the original amount that may have come from the plants that formed the coal.

The analyses given on p. 761 show that the mineral charcoal contains a smaller percentage of volatile matter and a larger percentage of fixed carbon than the average coal of the same bed. The proximate analyses (Table II) of the bright and dull laminae of the bituminous coal bed, cited by Pringle,[1] indicates that the dull laminae are similar in composition to mineral charcoal, as regards the smaller percentage of volatile matter, and the larger percentage of fixed carbon compared with the bright or the average coal.

TABLE II

	Water	Volatile Matter	Fixed Carbon	Ash
Dull laminae	1.68	14.71	77.17	6.44
Bright laminae	1.75	31.63	63.96	2.66

[1] John Pringle, *Trans. Edin. Geol. Soc.*, X, Pt. 1 (1912), 33.

Lesquereux[1] described the changes that occur in the vegetable matter at the surface of swamps during dry periods as follows:

> Wherever the growth of peat in submerged bogs is checked by dryness or other causes the upper surface of the peat becomes crusted, hardened, and transformed into a thin coating quite impervious to the entrance of any kind of foreign matter, and it is upon this hard upper crust that the boggy humus forms, or, whenever the land becomes resubmerged, a new peat vegetation begins. In such cases such a crust remains as a parting between two layers of peat.

Von Gumbel in 1883 suggested: "It is very probable that in occasional drying of the swamp, followed by renewal of flooding, lies the explanation of the alternating bright and dull coal bands."

In discussing the process of putrefaction of vegetable matter of coal as described by Renault, David White[2] says that if uninterrupted the process of putrefaction goes on until all the softer tissues are disintegrated and decomposed, leaving only the most indestructible parts, immersed in a dark subgelatinous, plastic, or liquid mass, the fundamental matter. This fundamental matter not only envelops the undestroyed woody matter, but it infiltrates the surviving tissues to a greater or less extent. Where the impregnation is complete, we find dense, glossy, and shining coal. In many instances the impregnation has been imperfect, and sometimes intergrades to a charcoal or "mother of coal."

It is thought by the writer that the oft-repeated lowering, probably of only a very few inches, of the water level in the shallow swamps, and the consequent exposure of successive levels of the vegetable matter to the air, is the only adequate explanation that accounts for the extensive bedding planes practically free from clay sediments, the general distribution and alternation of the bright and dull laminae, and the large amount of mineral charcoal in the latter, as they occur in the coal beds of Illinois, the bright laminae resulting from putrefaction entirely under water, and the dull laminae and mineral charcoal resulting from partial atmospheric decay previous to the more complete subaqueous putrefaction.

[1] L. Lesquereux, *Second Geological Survey of Pennsylvania, Ann. Rept. for 1885*, p. 118.

[2] David White, "Some Problems in the Formation of Coal," *Econ. Geol.*, III (1908), 303.

According to this view, the dull laminae and mineral charcoal partings of the coal beds are the records of repeated interruptions of accumulation, during which the surface of the vegetable material in the swamp was above water and exposed to atmospheric decay, resulting in the destruction of the softer parts of the plant tissues, leaving them in an indurated and more or less skeletonized and fibrous condition. On resubmergence these residual portions of the vegetable materials were not so readily impregnated with the fundamental matter of the bog as were those parts of the mass that had not suffered partial atmospheric decay, and hence are of dull appearance. Such periods of arrested accumulation of the plant material, due to the exposure of the surface of the vegetable matter of the bog, would be favorable for the accumulation on such a surface of a relatively larger proportion of spores than would be mingled with the vegetable mass during periods of submergence and of normal vegetable growth in the bog, and the resistant nature of the spore cases would permit their better preservation than the ordinary plant tissues during such times of exposure. These conditions would explain the greater abundance of spores in the dull than in the bright laminae of the coal beds. The variation in thickness of the dull laminae would be due to the unevenness of the surface of the exposed vegetable matter in the bog. The relatively smaller percentage of volatile matter and larger percentage of fixed carbon in the dull laminae and mineral charcoal would be explained in part by the fact that, during the times when the surface of the vegetable mass was above water and exposed to atmospheric decay, the volatile products of decomposition escaped into the air, and in part because the dull laminae were not subsequently infiltrated with the hydrocarbons of the fundamental matter to the same extent as the bright laminae.

The foregoing interpretation of the structural features of the coal beds leads to the following very definite conclusions:

1. That the beginning of vegetable accumulation of the coal beds was in a very shallow swamp.

2. That the swamp deepened so slowly, either by subsidence of the area or from the gradual building-up of the border or outlet by sedimentation, or both, that the plants were able to adjust them-

selves to the changes, and the accumulation of vegetable matter in a general way kept pace with the increasing depth.

3. That throughout the entire period of accumulation of the coal beds the water of the swamp was so shallow that during the oft-recurring cycles of drought successive levels of the vegetable mass were temporarily exposed and so modified by partial atmospheric decay as to result in the formation of the dull laminae with their mineral charcoal.

4. That the time involved in the accumulation of the vegetable material of a coal bed was the time necessary for the growth of the plants plus the time recorded in the interruptions of accumulation indicated by the dull laminae and charcoal partings of the coal, which would very greatly increase the usual estimate of time required.

BEREA SANDSTONE IN ERODED CLEVELAND SHALE[1]

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In Lorain County of northern Ohio occurs the greatest development of the Bedford-Berea unconformity.[2] This unconformity extends throughout other portions of the state.[3] It is found as channels over 100 ft. deep filled with Berea sandstone, as in the Amherst district, and from these pronounced forms declines in prominence to Berea sandstone filled channels 2–3 ft. deep, as that on Indian Creek at Stoneville, Ashtabula County, Ohio; or to a thin sandstone layer of the Bedford eroded away in the center where it crosses Phelps Creek, southeast of Painesville, Ohio.[4]

All of the channels eroded in the Bedford formation have either been confined to that formation, or have started in the Bedford and penetrated into the Cleveland formation which lies below the Bedford. These channels eventually were filled with Berea sand which, on consolidating, formed the Berea sandstone.

The most northerly Berea sandstone in Ohio.—The most northerly occurrence of Berea sandstone is that outcropping on the shore of Lake Erie, two miles east of Vermilion, Lorain County. Here the Berea sandstone extends from the top of a 25-ft. lake-cliff to the water's edge, under which it dips.

As far as the writer is aware, the first and only mention ever made of this body of Berea sandstone was made by E. M. Kindle

[1] Published by permission of the Director of the Ohio State Geological Survey. Read before the Twenty-third Annual Meeting of the Ohio Academy of Science, at Oberlin, Ohio, November 29, 1913.

[2] W. G. Burroughs, "The Unconformity between the Bedford and Berea Formations of Northern Ohio," *Jour. Geol.*, XIX, No. 7 (1911), 655–59.

[3] Charles S. Prosser, "The Disconformity between the Bedford and Berea Formations in Central Ohio," *Jour. Geol.*, XX, No. 7 (1912); Charles S. Prosser, *Geol. Surv. Ohio, Bull. 15*, Fourth Series; H. P. Cushing, manuscript.

[4] Charles S. Prosser, *Geol. Surv. Ohio, Bull. 15*, Fourth Series, p. 277, and B, of Plate XVII, p. 274.

who ascribed its position to faulting.[1] Kindle stated that "in the vicinity of Lorain and for several miles to the westward, the shales [Cleveland] are concealed along the lake by glacial deposits. The shale cliffs reappear again, however, near the mouth of the Vermilion River. Here along the shore east of the river, broad, low anticlinal rolls prevail. These are interrupted by a fault which brings the Berea sandstone down to lake level and beneath which it dips at 45 degrees."

The writer wishes to advance another theory than that of faulting, for the occurrence of the Berea sandstone in the place which it occupies in the Cleveland shale; but first, a detailed description of the geology of this locality is necessary.

The Berea sandstone is composed of massive beds 10–15 ft. thick, with a total height of 20–30 ft. from the water's edge to the highest point of sandstone; the average would be about 25 ft. On the horizontal, the sandstone extends about 100 ft. It dips beneath the lake at an angle of 45 degrees. The stone, itself, is gray, with a moderately coarse grain.

West of the Berea sandstone there is no outcropping of rock for about 200 yds., when the Cleveland shale, that elsewhere forms the lake-cliffs of this region, again comes to the surface and continues westward as the lake-cliff. The covered area is composed of glacial drift.

On the east side of the sandstone, soft, blue-gray shale extends from the lake beach up the lake-cliff, until near the top of the bank the gray shale turns reddish in color. This reddish shale, however, is due to oxidation, for on digging into it, the gray shale is found at a depth of 5 in. from the surface. The red shale is simply oxidized gray shale. The shale is capped by drift, 5 ft. thick.

A concretionary sandstone layer, 1 ft. thick, occurs interbedded in the gray shale at about 20 ft. vertically up the bank when first seen beside the Berea sandstone. The gray shale and the concretionary sandstone layer extend eastward 75 ft. on the horizontal, when they are covered for 125 ft. by drift. At the end of the

[1] E. M. Kindle, "Stratigraphic Relations of the Devonian Shales of Northern Ohio," *American Journal of Science*, August, 1912, pp. 187–213. For reference to quotation see p. 208.

covered area, the Cleveland appears, forming the customary Cleveland shale lake-cliff. Here, where the cliff is formed of the Cleveland formation, the Cleveland shale is thin-bedded with very fine, knifelike edges, black and brittle. Interbedded in this type of Cleveland shale is a 5-ft. bed of soft, thin-bedded, greenish-gray shale, which resembles closely the gray shale beside the Berea sandstone. This greenish-gray shale of the Cleveland is not the same as the shale beside the Berea sandstone, however, for where last exposed the concretionary layer, above mentioned, at this point 12 ft. vertically above the beach, was dipping eastward toward the greenish-gray Cleveland shale 125 ft. horizontally away. But no sandstone layer occurs in the greenish-gray Cleveland, nor in the black Cleveland, whatsoever. The concretionary sandstone layer ceased to exist when the Cleveland was reached. Hence the two gray shales are not the same.

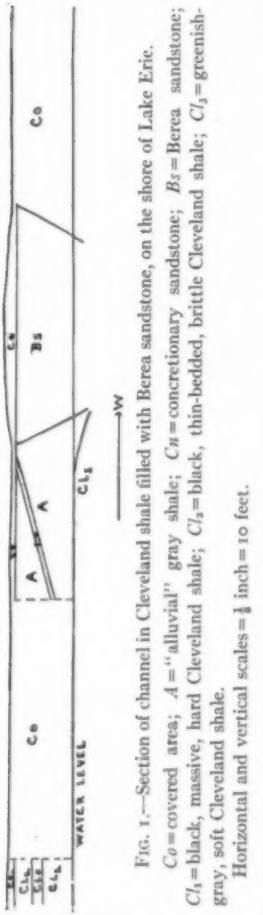

FIG. 1.—Section of channel in Cleveland shale filled with Berea sandstone, on the shore of Lake Erie.
Co = covered area; *A* = "alluvial" gray shale; *Cn* = concretionary sandstone; *Bs* = Berea sandstone; *Cl*$_1$ = black, massive, hard Cleveland shale; *Cl*$_3$ = black, thin-bedded, brittle Cleveland shale; *Cl*$_2$ = greenish-gray, soft Cleveland shale.
Horizontal and vertical scales = $\frac{1}{8}$ inch = 10 feet.

Going once more back to the Berea sandstone, we find at the water's edge, under the gray shale, a jet black, rather massive Cleveland shale, harder and heavier than the Cleveland shale forming the lake-cliffs to the east. This massive Cleveland shale starting 25 ft. to the east of the Berea sandstone dips westward toward the sandstone at an angle which will cause the base of the Berea to be less than 10 ft. below the surface of the lake at the point where it dips under the water. The Cleveland and Berea are within a few feet of each other when the Cleveland dips beneath the lake under the Berea. No

other rock appears to be between the Berea sandstone and the massive Cleveland shale.

The Berea sandstone narrows somewhat in its horizontal dimensions as it descends toward the Cleveland shale beneath. Its sides, though somewhat covered, present the appearance of the sloping sides of a channel, such as is seen where the Berea sandstone fills a channel in the eroded horizon of the Bedford shale. West of the sandstone the lake sands cover the massive Cleveland shale.

One-half mile, slightly to the west of south from this Berea sandstone on the lake shore, gray, moderately coarse-grained Berea sandstone beds one inch to one foot thick outcrop from the bank on the south side of the electric car line. The total height of the exposure is 5–10 ft., and the horizontal distance about 100 ft. The formation is dipping 6 degrees toward S., 18 degrees E., and striking N. 72 degrees E. A few yards to the north, black, thin-bedded Cleveland shale comes to the surface in the ditch beside the New York, Chicago & St. Louis Railroad track. The vertical distance between the Berea and Cleveland outcrops is less than 10 ft. The exact contact is covered.

South of this Berea sandstone outcrop, 100 yds., is an abandoned Berea sandstone quarry, its bottom filled with water and débris. The depth of the sandstone to the water is 20 ft. The pit is about 125 ft. square. The sandstone is gray, moderately coarse grained, beds 8 ft. thick. The top 5–10 ft. of the formation are of thin-bedded sandstone layers, capped by 1–3 ft. of clay. The amount of area underlain by this Berea sandstone appears, from surface indications (for save in the places mentioned the clay drift covers the sandstone), to be 8–10 acres.

Two miles south of this sandstone, along the Lake Shore & Michigan Southern Railroad tracks, the rock is entirely Cleveland shale, and continues to be Cleveland shale until farther south we get the overlying main body of Bedford shale and Berea sandstone. The nearest portion of Berea sandstone to the Berea sandstone in which the quarry is situated, and to that along the lake, is the main body of the Berea formation 2 miles southeast of the quarry, and $2\frac{1}{2}$ miles southeast of the Berea sandstone on Lake Erie.

THE HYPOTHESIS OF FAULTING

Now, if these isolated bodies of Berea sandstone owe their present position to faulting, the downward movement, as measured by present horizons, must have been an approximate vertical displacement of 120 ft., for that is the vertical distance between the base of the nearest portion of the main body of the Berea formation, and the base of the Berea sandstone dipping under Lake Erie. This is a very great throw for this region where all other vertical displacements, as far as the writer is aware, are less than 75 ft. at the most. Also, the presence of several acres of sandstone one-half mile to the south of the sandstone on the lake shore, would hardly have occurred in such quantity through the gentle faulting to which these regions of northern Ohio have been subjected.

BEREA SANDSTONE IN ERODED CLEVELAND SHALE

The writer advances the following theory for the formation of these isolated and most northerly bodies of Berea sandstone:

At the same period when the deep channels in the Bedford shale of the Amherst district, $5\frac{1}{2}$ miles to the southeast, were being cut, a stream, as shown by the exposed gray shale and Berea sandstone, cut a channel 175 ft. wide (and without doubt a far greater width could be proven if the outcrops were not covered) into the Cleveland shales.

The Cleveland shale of this district was thus a land area at probably the same time that the Bedford to the south was above the level of the sea. When deposition took the place of erosion, alluvial sediments were deposited in this channel in the Cleveland shale. These sediments later formed the soft gray shale, previously described. The concretionary sandstone bed was laid down at the time these alluvial gray sediments were deposited. As occurs in certain of the Bedford channels, the deposited material slumped toward the sides of the channel, which accounts for the dip of the concretionary sandstone bed toward the Cleveland shale which formed the side of its channel.

Later, the soft alluvial material was worn away to some extent and the Berea sands deposited in the channel thus formed. The

slanting side of the Berea sandstone at its contact with the gray shale of the present day marks the side of this old channel.

THE BEDFORD-BEREA UNCONFORMITY AND THE DEVONIAN-CARBONIFEROUS LINE

Some geologists have questioned the erosion of the Bedford formation prior to the deposition of the Berea, as being of much value in determining the position of the Devonian-Carboniferous line. They argue that the time would be very short indeed, geologically, in order that the soft Bedford shale might be worn away to the extent which we find it, and that the cycle of erosion would therefore be of very slight importance.

Hence, an eroded channel in the Cleveland shale of the magnitude of the one described should help to show that the period of erosion of the Bedford was of much longer duration than was to be inferred by the channels in the soft Bedford shale, for the rather hard Cleveland shale is not especially easy to erode. The time required in the removal of the Cleveland would be far greater than that required in any of the Bedford channels.

Therefore, the interval of erosion of the Bedford prior to the Berea deposition was of greater length than has been shown by any other evidence set forth up to the present time.

Consequently, the Berea sandstone filled channel in the eroded horizon of the Cleveland shale acts as evidence in favor of placing the Devonian-Carboniferous line between the Bedford and Berea formations.

THE AVERAGE IGNEOUS ROCK

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University of Wisconsin

The chemical composition of the average igneous or crystalline rock of the earth's crust is of sufficient interest to geologists and petrographers to have elicited several attempts at compiling average analyses. Clarke[1] summarizes the three most important averages of igneous rock analyses—those by Clarke, by Harker, and by Washington. These averages agree fairly well, showing very small differences in the amounts of the various oxides, and there is little to be said of the relative merits of the three determinations.

One question, however, has been repeatedly raised, i.e.: Does the average of all igneous rock analyses represent with any degree of certainty the actual average of the igneous rocks of the earth's shell? Obviously, if the average analyses of Clarke, Harker, and Washington are to represent correctly the composition of the igneous rocks of the earth's crust, it is necessary that the samples of the various types of igneous rock be proportional to the amounts of these several types in the earth's crust. If not, these average analyses are misleading.

In the course of certain investigations in the Metamorphic Laboratory at the University of Wisconsin, the writer has attempted to check Clarke's average igneous rock by comparing it with the composition of the sediments, and the results obtained are thought to be of sufficient interest to warrant their presentation here.

If we are correct in the assumption that the oxides of the bases and the silica of the sediments have as their ultimate source the igneous rocks, then a properly weighted average of the sediments (excluding water and carbon dioxide) would represent very closely the average composition of the igneous rocks from which these sediments were derived. Certain discrepancies are to be expected

[1] F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Survey, Bull. 491*, 1911.

owing to the segregation of certain constituents, such as the mineral matter in the sea and certain mineral deposits not included in the sedimentary rocks. The solution of this problem was attempted by the writer and the results published in this journal.[1]

The former problem may be briefly stated as follows: given, the average composition of the igneous rocks and of the shales, sandstones, and limestones; to find the relative abundance of these three important types of sediments. The present problem, while somewhat similar, differs materially, and may be stated as follows: assuming that the average igneous rock may be closely approximated in composition by some combination of average granite and average basalt, what ratio of granite to basalt best explains the composition of the sediments as expressed by average analyses of the shales, sandstones, and limestones, respectively; and simultaneously with this solution, what ratio of shale, sandstone, and limestone would result from the redistribution of this combination of granite and basalt? The above might be stated in the form of an equation as follows:

> x granite$+y$ basalt$=a$ shale$+b$ sandstone$+c$ limestone, given average analyses of granite, basalt, shale, sandstone, and limestone to solve for x, y, a, b, c.

Note that no assumption is made as to the relative abundance of shale, sandstone, and limestone, and that the solution of the problem is based in no way on the results previously obtained[2] *or on any assumption as to the average composition of the igneous rocks.* The data used in this problem are given in Table I. The average granite and average basalt, columns 1 and 2, are those compiled by Dr. Daly.[3] The average analyses of the shales, sandstones, and limestones, respectively, are those compiled by Clarke.[4] Since the water and carbon dioxide of the sediments are for the most part derived from the hydrosphere and atmosphere, it is necessary in this problem

[1] W. J. Mead, "Redistribution of Elements in the Formation of Sedimentary Rocks," *Jour. Geol.*, XV (1907), 238–56.

[2] W. J. Mead, *op. cit.*

[3] R. A. Daly, "Average Chemical Compositions of Igneous-Rock Types," *Proc. Amer. Acad. Arts and Sciences*, XLV (1910), 211–40.

[4] F. W. Clarke, *op. cit.*, p. 28.

to recalculate the analyses of the sediments, excluding these constituents. The analyses of the igneous rocks are recalculated on a water-free basis. Since the problem does not permit of a rigorous solution, graphic methods have been used which permit of viewing in perspective, as it were, the various relations and conceptions involved.

TABLE I

	1	2	3	4	5	6	7	8
SiO_2	70.47	49.65	58.38	64.00	78.66	83.95	5.19	9.02
Al_2O_3	14.90	16.13	15.47	16.94	4.78	5.10	.81	1.41
Fe_2O_3	1.63	5.47	4.03	4.42	1.08	1.15	.54	.94
FeO	1.68	6.45	2.46	2.69	.30	.32		
MgO	.98	6.14	2.45	2.68	1.17	1.25	7.90	13.74
CaO	2.17	9.07	3.12	3.42	5.52	5.90	42.61	74.10
Na_2O	3.31	3.24	1.31	1.43	.45	.48	.05	.09
K_2O	4.10	1.66	3.25	3.56	1.32	1.41	.33	.57
TiO^2	.39	1.41	.65	.71	.25	.27	.06	.10
P_2O_5	.24	.48	.17	.19	.08	.085	.04	.07
Totals	99.87	99.70	91.29	100.04	93.61	99.915	57.53	100.04
Fe	2.45	8.86	.....	5.19	.....	1.055	.....	.66

1. Average granite.
2. Average basalt.
3. Average shale.
4. Average shale recalculated to 100 per cent, omitting H_2O and CO_2.
5. Average sandstone.
6. Average sandstone recalculated to 100 per cent, omitting H_2O and CO_2.
7. Average limestone.
8. Average limestone recalculated to 100 per cent, omitting H_2O and CO_2.

Trilinear co-ordinates are used in Fig. 1; the triangle labeled in the corners "Shale," "Limestone," and "Sandstone," respectively, serves as a base on which ratios of these three components may be indicated by points, and a series of ratios represented by lines. The algebraic sum of the perpendicular distances from any point inside or outside of the triangle to the three sides of the triangle or their extensions equals the altitude of the triangle, considering distances toward the opposite apex as positive, and distances away from the opposite apex as negative. *Any point on the dotted line labeled "SiO_2, Gr." represents in parts per hundred the ratio in which shale, sandstone, and limestone may be combined to yield the same amount of silica as the average granite.* This line is obtained by finding the proportion in which sandstone and lime-

stone combine to yield the same percentage of silica as the average granite, and also the proportion in which shale and limestone combine to the same end. These points platted on the sides of

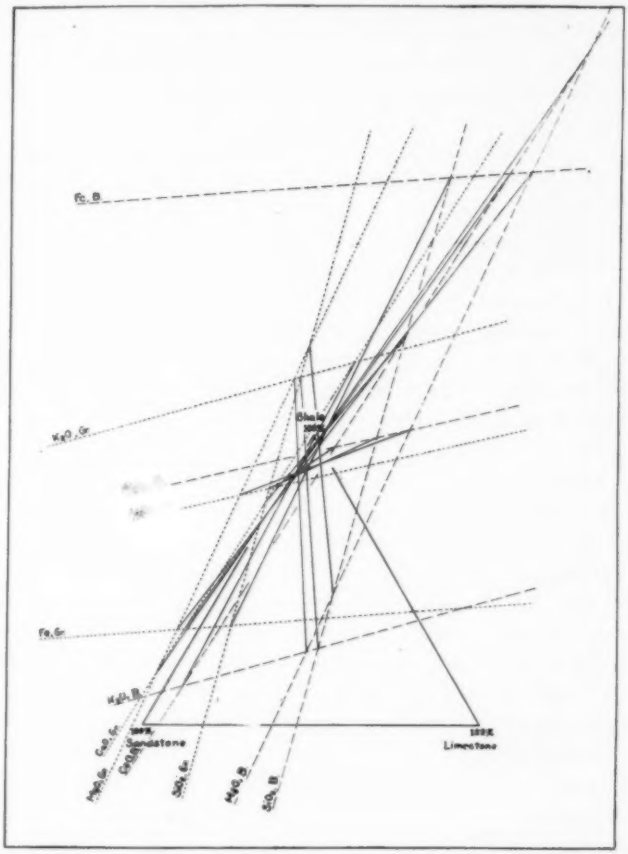

FIG. 1.—Graphical expression of the relations of any combination of granite and basalt and the ratios of sediments derived from them.

the triangle determine the line. In a similar manner lines are drawn for the various oxides[1] for both the average granite and the

[1] Iron is calculated as total Fe, the oxides not being considered separately.

average basalt. The very low soda content of the sediments due to the segregation of that constituent in the sea causes the soda line to fall too far outside the triangle to be shown. If the sediments were derived from the average granite, the lines of the several oxides would come very close to intersecting at a point, but since this is not true, the lines for granite are widely distributed and their intersections fall over a wide area. This is likewise true of the basalt lines.

The point of intersection of the dotted silica and alumina lines indicates the ratio of shale, sandstone, and limestone containing the same amount of silica and alumina as the average granite. Similarly the intersection of the broken silica and alumina lines indicates the ratio of shale, sandstone, and limestone containing the same amount of silica and alumina as the average basalt. *The line connecting these two points of intersection is the locus of the intersections of the silica and alumina lines for any combination of granite and basalt.* In this manner lines connecting similar intersections of granite und basalt lines have been drawn. *If the sediments were derived from some combination of granite and basalt, these lines connecting intersections should intersect at a common point.* However, because of the nature of the data, we may expect at best that these lines will intersect within a small area. An examination of the diagram, Fig. 1, shows that this is exactly what happens; i.e., there is a distinct tendency for these lines to converge and intersect within a limited area. If the lines connecting intersections crossed each other at a common point, the ratio of granite to basalt would be measured by the ratio of the distances from the point of intersection to the "granite" and "basalt" ends of the lines respectively.

In order to determine whether there is any tendency toward the expression of a definite ratio of granite to basalt by the grouping of the points of intersection on each of the several connecting lines, these lines have been transferred from Fig. 1 to Fig. 2, where by means of a proportional triangle each line is automatically divided into ten equal parts. The points of intersection of any line with the other lines are marked by short lines crossing the line considered. Inspection of the proportional triangle on which these

lines have been placed shows that there is marked uniformity in the ratio of granite to basalt, as expressed by the positions of intersection on these several lines. The average of the ratios expressed by the points of intersection on each line has been indicated by a large dot near the line, and the positions of these dots on the scale

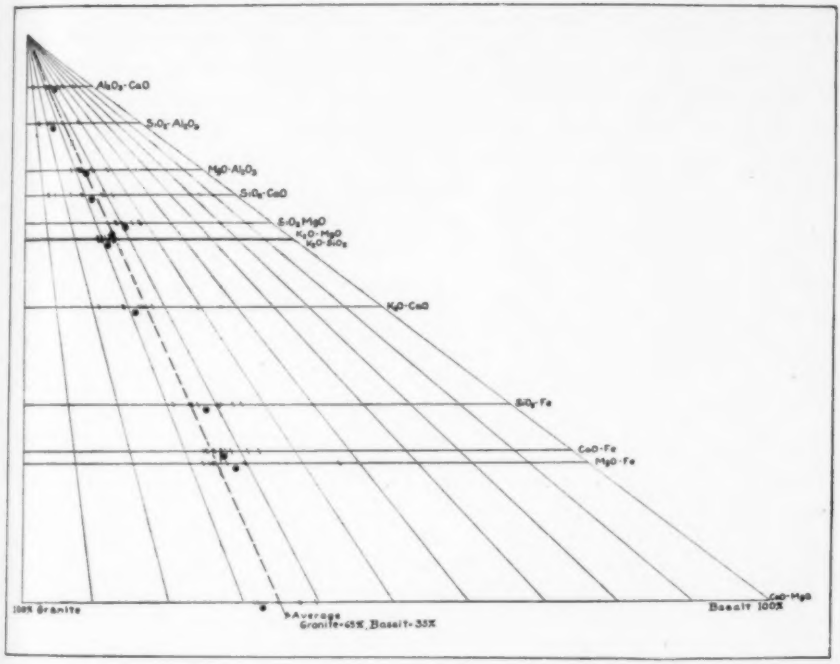

FIG. 2.—Proportional triangle used as a scale on which to measure the granite-basalt ratios expressed by the position of intersections on the full black lines in Fig. 1.

of the proportional triangle show a distinct concordance. By averaging the ratios expressed by the dots on the several lines, the average ratio of granite to basalt is found to be 65 parts granite to 35 parts basalt, i.e., this is the proportion of granite to basalt which may be most closely approximated by some combination of derived sediments represented by their average analyses here employed.

This solution assumes that the average analyses of granite, basalts, shales, limestones, and sandstones used are approximately correct, and that the average igneous rock may be represented by some combination of granite and basalt. So far as these assumptions are not true, solution fails, but the fact that the graphical method admits of selecting a definite ratio of granite and basalt and that this ratio yields an average so similar to the average for the igneous rock obtained by Clarke and others seems to indicate that the data and assumptions are not in serious error.

In Table II, column 1 is the average analysis obtained by combining the average granite and the average basalt in this ratio. For purposes of comparison the average analyses of igneous rocks obtained by Clarke, Harker, and Washington are placed in parallel columns.

TABLE II

	1	2*	3	4	5*	6*
SiO_2	62.18	61.82	+1.36	+2.2	60.76	58.96
Al_2O_3	15.35	15.51	− .16	−1.03	15.87	15.99
Fe_2O_3	2.97	2.67	+ .20	+ 7.5	4.92	3.37
FeO	3.35	3.45	− .10	− 2.9	2.78	3.93
MgO	2.79	4.02	−1.23	−30.5	3.82	3.89
CaO	4.58	4.96	− .38	− 8.45	4.97	5.28
Na_2O	3.28	3.51	− .23	− 6.5	3.28	3.96
K_2O	3.24	3.04	+ .20	+ 6.6	2.85	3.20

* F. W. Clarke, *op. cit.*, p. 25.

1. Average granite and average basalt, combined in ratio of 65 to 35.
2. Clarke's average igneous rock.
3. Differences between 1 and 2, on basis of total rock.
4. Differences between 1 and 2, in percentage for each constituent.
5. Harker's average igneous rock.
6. Washington's average igneous rock.

The differences between column 1 and the three average analyses of igneous rocks are small. The differences between column 1 and Clarke's average igneous rock are expressed in terms of the entire rock and in percentage of each constituent in columns 3 and 4 respectively. The most striking result of the comparison is the marked similarity between the combined granite and basalt and the average analyses. The greatest differences are for silica and magnesia, the combination of granite and basalt being slightly more acidic than the other averages.

The most important conclusion is that the average analyses of Clarke, Harker, and Washington are closely checked by this method, and that of the three analyses Clarke's average is most closely approximated. The nature of the data obviously does not permit of drawing any definite conclusions as to the cause of the slight differences between Clarke's averages and the averages here obtained.

The greatest difference occurs for MgO, the combined granite basalt showing 30.5 per cent less MgO than Clarke's average. This difference is so much greater than for any of the other oxides that it may be of significance. It is possible that igneous rocks collected largely for petrographic purposes would include the unusual and interesting alkaline and ultra-basic types, the syenites, peridotites, etc., in an amount out of proportion to their abundance as compared with the more common granite and basalt types. The alkalies, lime, silica, and alumina would not be materially affected by this, as the alkaline rocks would offset the basic varieties, but the range of MgO content being much greater (varying from 1 per cent or less in the alkaline rocks to 30–40 per cent in the peridotites), this oxide would tend to be increased by the inclusion of an excess of the less common rocks.

Ratio of shale, sandstone, and limestone.—The foregoing solution, while yielding rather definitely the ratio of granite and basalt best explaining the composition of the sediments, simultaneously yields the ratio of shale, sandstone, and limestone resulting from the redistribution of this hypothetical average igneous rock. In Fig. 3 the lines for the several oxides were obtained by drawing lines parallel and between the granite and basalt lines on Fig. 1, at distances representing the 65–35 ratio. These lines in Fig. 3 intersect within a small area and a point at the center of this area expresses a ratio of 88 parts shale, 9 parts sandstone, and 3 parts limestone. Since water and carbon dioxide were excluded from the analyses of the sediments in obtaining these ratios, it is necessary to recalculate to include these constituents, which gives 87 parts shale, 8 parts sandstone, and 5 parts limestone. This ratio differs from the ratio of 80:11:9 previously obtained by the writer,[1]

[1] W. J. Mead, *op. cit.*

by showing more shale, less sandstone, and less limestone, but in a general way is similar in showing the great predominance of shale over the other two sediments.

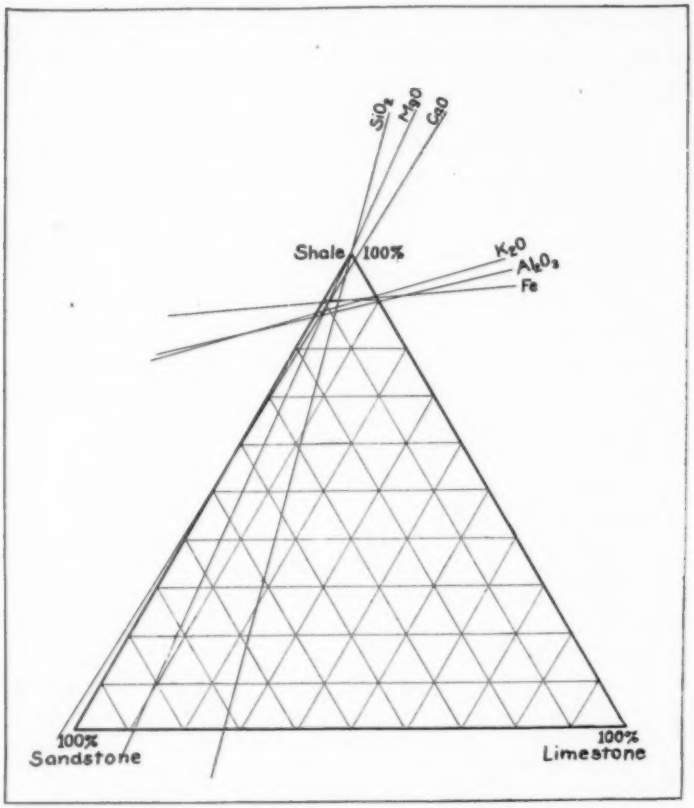

FIG. 3.—The lines on the triangle show for each constituent the proportions in which the three sediments combine to yield the same amount of that constituent as the combination of 65 parts granite and 35 parts basalt. Compare with Fig. 4.

A further comparison of the combined granite and basalt with Clarke's average igneous rock is afforded by comparing Fig. 4 (which represents for Clarke's average exactly what Fig. 3 represents

for the combined granite and basalt) with Fig. 3. The lines in Fig. 3 intersect within a much smaller area than in Fig. 4, which

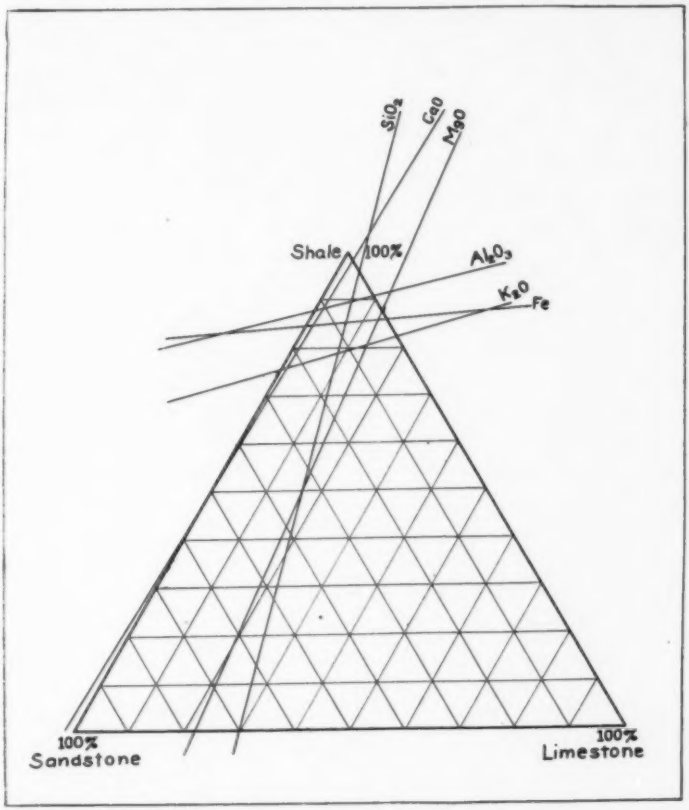

FIG. 4.—The lines on the triangle show for each constituent the proportions in which the three sediments combine to yield the same amount of that constituent as Clarke's average igneous rock. Compare with Fig. 3.

is simply another way of expressing the closer accordance of the granite basalt average with the sediments as compared with Clarke's.

EOCENE HORIZONS OF CALIFORNIA

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During the past few years geologists of California have been devoting considerable attention to the Eocene, with the result that three horizons are now recognizable. In order of their deposition these are the Martinez, Tejon, and Ione formations.

MARTINEZ FORMATION

The Martinez formation has so far been found in the Mt. Diablo region, Contra Costa County; in the Santa Monica Mountains, northwest of Los Angeles; and on the west side of the Santa Ana Mountains. It is characterized by sandstones and shales, not unlike those of the Chico (Upper Cretaceous) formation, and by a fauna strikingly similar to those of the eastern Midway formation, with which it is to be correlated. In the Santa Monica Mountains it is characterized by *Venericardia planicosta* var. *venturensis* var. nova, which is similar to *V. planicosta* Harris.[1] Several other new species have also been found, the most characteristic of which here described are from the Santa Monica Mountains.

Crassatellites branneri n.sp.—Shell about 55 mm. high, trigonal, slightly longer than high; beaks subcentral, prominent, deeply excavated front and back, incurved, with sides sloping equally and rapidly, most abrupt in advance, slightly convex behind; lunule cordate; anterior end broadly rounded; posterior truncated and flattened from the umbonal ridge to the cardinal and posterior margins. Surface marked by lines of growth and fine radiating lines which are especially apparent in worn specimens. Leland Stanford Junior University Paleontological Collection. Named in honor of Dr. J. C. Branner.

Lima perrini n.sp.—This giant circular lima has a thick shell with nacreous, and outer prismatic layer. The diameter is about

[1] *Bull. Am. Pal.*, No. 4, p. 58, Fig. 13.

160 mm. The umbones are small and the cardinal margin slopes gradually to the posterior where it becomes rounded and grades into the circular margin below. The beaks are slightly excavated in front, and the margin slopes at a 35-degree angle into the rounded anterior margin. The hinge is very thick and has a deep wedge-shaped ligament pit sloping from the interior edge of the shell to the exterior edge at the anterior end of the hinge line. A single large sub-posterior muscle impression marks the interior of the shell. The surface is ornamented by many fine radiating lines, and the prismatic shell layer gives the surface a silken appearance. It belongs to the subgenus Acesta. Leland Stanford Junior University Paleontological Collection. Named in honor of Dr. J. Perrin Smith of Stanford University.

Pseudoliva reticulata n.sp.—Shell subconical, whorls four, spire low, suture linear. Altitude 20 mm., width 12 mm. Inner whorls almost covered by body whorl, which is concave. Aperture wide, posterior angular, anterior produced slightly into a canal. Outer lip simple, inner lip incrusted and marked by a fold revolving from the end of the canal around to the inner lip, representing the former positions of the end of the canal. Surface ornamented by longitudinal folds and spiral ribs; where these intersect, small tubercles develop. The middle of the body whorl is impressed by a single revolving line which forms a tooth where it is truncated on the outer lip. Leland Stanford Junior University Paleontological Collection.

Turritella maccreadyi n.sp.—Shell robust, apical angle broad; whorls eleven, rounded, with six or seven strong, nearly equally spaced, spiral ribs. The first five or six whorls are angulated like *T. martinezensis* Gb.[1] Surface below body whorl also ornamented by spiral lines, and whole surface marked by lines of growth. Aperture broad, outer lip slightly sinuous; inner lip sinuous, flattened, and twisted. Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. George McCready of Guanoco, Venezuela.

Nautilus hallidayi n.sp.—Shell immense, being about 36 mm. in greatest diameter. The inner whorls are completely enveloped,

[1] *Geol. Surv. of California*, Paleontology, Vol. II, p. 169, Pl. 28, Fig. 51.

while the last whorl is more evolute. Dorsum rounded. Aperture elliptical, concave below where it envelops the early coils. The outer volution has a width slightly less than the remaining diameter of the shell. Sutures slightly inflected. Shell pearly. It is probably the oldest species of true nautilus known. Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. T. W. Halliday of Spokane, Washington.

TEJON FORMATION

The Tejon formation occurs principally in Kern, Santa Barbara, Ventura, and Los Angeles counties, with a fringe along the eastern flank of the southern end of the Mt. Diablo Range. Smaller patches outcrop near the coast north of San Diego and in the Santa Ana Mountains. The formation consists of conglomerates, sandstones, and shales, and faunally is characterized by *Turritella uvasana* Conrad, *Morio tuberculatus* Gb., and *Venericardia planicosta* var. *horni*. Gb., which is very similar to *V. planicosta* var. *regia* Conrad of the Aquia formation of Maryland. Several new species have been found, the most striking among which are the following:

Cucullaea morani n.sp.—Shell thick, oblique, very convex; beaks large, broad, prominent, and about one-third the distance from the anterior, incurved and somewhat remote; area oval in shape and about two-thirds the length of the shell. Altitude 36 mm.; longitude 60 mm. Anterior margin broadly rounded and more prominent above; base nearly straight; posterior produced and sharply rounded; umbonal ridge prominent and runs to posterior margin; cardinal margin sloping at an angle of about 45 degrees. Surface marked by alternating single and double radiating ribs which are crossed by fine to coarse lines of growth. Locality one and one-half miles east of McCray Wells, Ventura County. Specimens in Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. R. B. Moran of San Francisco.

Isocardia tejonensis n.sp.—Shell of medium size, thin; valves equal, inflated, rotund, completely closed, margins plain; beaks prosogyrous. Surface marked by concentric bandlike ribs, which

become fine and nearly obsolete on the beaks. From one and one-half miles east of the McCray Wells, Ventura County. Specimens in Leland Stanford Junior University Paleontological Collection. This is the first species of *Isocardia* described from the Eocene of California.

Pinna lewisi n.sp.—Shell thin, pearly, mytiliform, equivalve, truncate, and wholly open behind, hinge line long; valves triangular, the apical angle being about 45 degrees; convex along the center line and flaring at the margins. Base of shell notched in the middle and convex on either side. Surface marked by five indistinct radiating ribs and concentric lines of growth. From one and one-half miles east of McCray Wells, Ventura County. Specimen in Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. J. O. Lewis of San Francisco.

IONE FORMATION

The Ione formation is typically represented on the east side of the San Joaquin Valley, extending from a point twenty miles east of Merced to a point forty miles south of Auburn. It is to be correlated with the marine Eocene sediments of Corral Hollow, those in the northern part of the Mt. Diablo Range, and with those on the eastern flank of the St. Helena Range. The formation is characterized by clayey shales and sandstones and by such fauna as *Turritella merriami* Dickerson[1] and *Venericardia planicosta* var. *ionense* var. nova, which is similar to *V. marylandica* Harris[2] and *V. potopacoensis* Harris.[3] The formation is probably to be correlated with the Nanjemoy, which, it is thought by Harris, ranges higher than Chickasawan and Upper Lignitic.

The three horizons each have typical faunas among which the *Venericardia* and *Turritella* are represented by very characteristic species. The evolution of *Venericardia planicosta* Lamarck seems to have been from a square-ribbed variety to one with broad, rounded ribs, and then finally to a smooth form. Conditions were favorable for its more rapid evolution during the Tejon period and a wide range of variation is noted.

[1] *Bull. Dept. Geol., Univ. of Calif.*, Vol. VII, No. 12 (April, 1913), p. 284, Pl. 13, Fig. 6.

[2] *Maryland Geol. Surv.*, "Eocene," pp. 178–79, Pl. XI, Figs. 4–7. [3] *Ibid.*

CONTEMPORANEOUS DEFORMATION: A CRITERION FOR AQUEO-GLACIAL SEDIMENTATION

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Previous records of deformation in unconsolidated strata.—Deformation in unconsolidated strata has been observed and recorded by many writers on geological subjects. Faults having a displacement ranging from a fraction of an inch to a few feet are often seen in sections of glacial sandplains, eskers and kames, and in river terrace deposits.[1] Being due probably to removal of some lateral or subjacent supporting material, these faults are nearly always of the normal type. Folds in unconsolidated sediments are of much less common occurrence. J. B. Woodworth has figured and described such deformation in the kame gravels west of Fresh Pond, in Cambridge, Massachusetts.[2] These folds, having a height of as much as 10 feet, were overturned southward in a way to indicate that they had been formed by the thrust of a readvancing ice lobe. The same features were described a few years earlier by Woodworth and Marbut.[3] Similarly, contortion in the Columbia formation on Martha's Vineyard and Block Island has been ascribed to the pressure exerted by overriding Pleistocene ice.[4]

In all the instances noted above the deformation was in no way associated with the deposition of the beds. It was distinctly subsequent in point of origin. In the pages that follow is described a

[1] The present writer described one good example of this phenomenon several years ago (*Science* [IV], XXVIII [1908], 654).

[2] *Essex Institute Bull.*, XXIX (1898), 71.

[3] *U.S. Geol. Survey, Ann. Rept. 17* (1896), Pt. 1, p. 990.

[4] J. B. Woodworth, "Unconformities of Martha's Vineyard and of Block Island," *Bull. Geol. Soc. Am.*, VIII (1897), 197–212; "Glacial Origin of Older Pleistocene in Gay Head Cliffs . . . . ," *ibid.*, XI (1900), pp. 455–60. Shaler, at an earlier date, believed these folds were of orogenic origin. See, e.g., his "Report on the Geology of Martha's Vineyard," *U.S. Geol. Survey, Ann. Rept. 7* (1888), p. 345; and his "Tertiary and Cretaceous Deposits of Eastern Massachusetts," *Bull. Geol. Soc. Am.*, I (1890), 446–47.

kind of distortion, which is believed to have been contemporaneous with the accumulation of the strata.[1]

The Squantum slates described.—On the eastern coast of Squantum Head, in Boston Harbor, Massachusetts, is a series of slates

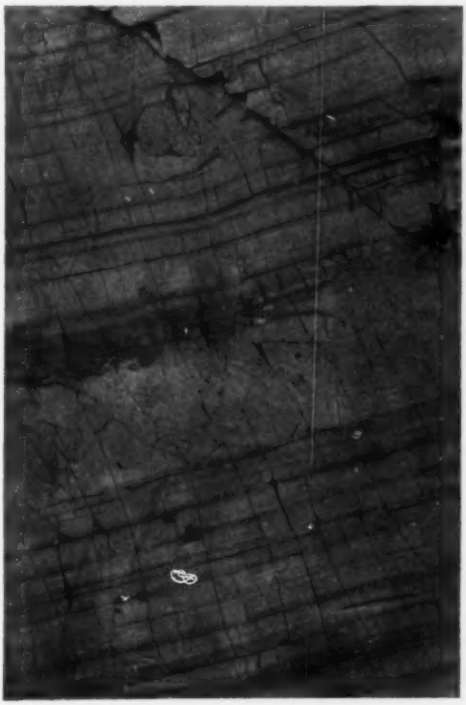

FIG. 1.—The Squantum banded slates. Near the middle of the picture is a zone in which the strata have been closely folded. Above this zone may be seen an isolated pebble, about three inches in diameter, which is thought to have been dropped by floating ice.

overlying the Squantum tillite.[2] The formation is of late Carboniferous or of Permian age. The slates are very fine-grained

[1] The same type of distortion was described by James Geikie in clay beds overlying till at Portobello, Scotland; see his *Great Ice Age* (3d ed., New York, 1895), pp. 271–74.

[2] R. W. Sayles, "The Squantum Tillite," *Bull. Mus. Comp. Zoöl.*, LVI, No. 2 (1914), 141–75.

sandstones and coarse and fine mudstones. These variations in texture are frequent, thus giving rise to a very uniform, closely spaced bedding lamination or banding (see Fig. 1). The strata have a pretty regular southeastward dip of 20°–25°. Minor undulations are seen here and there, but these are easily recognized as of orogenic origin and were no doubt formed at the same time with the larger deformation of which the inclination of the beds is evidence.

FIG. 2.—Hand specimen of the truncated folds seen at Squantum. Here the folds are not very strongly overturned. The length of the specimen illustrated in the figure is about eight inches.

At several stratigraphic levels in the series, at intervals of a few feet, are belts or zones in which the primary banding has been compressed into small folds (Fig. 1). Downward in the strata these folds diminish in size until they disappear, i.e., they grade into unfolded beds (Fig. 2). Above, they are sharply truncated by beds of similar nature, which have not been distorted. The little folds are all overturned in the same direction. Sometimes the overturning is slight, as in the figure. At other times the overturning may actually pass into overthrust faults having a displacement

of an inch or two. Zones showing this sort of distortion are not at all uncommon in the finer clastics of Squantum Peninsula.

Inferences as to the origin of the Squantum slates.—The characters of the Squantum slate series suggest the following conditions of origin: (1) Muds and silts were quietly accumulated in a body of water practically unaffected by currents, or, at least, by changing currents. (2) Occasionally a rigid body, submerged deep enough to touch bottom in places, floated by and here and there rubbed over

FIG. 3.—Contemporaneous deformation seen in unconsolidated sand at Woodland. The folds are truncated and overlain by horizontal strata as at Squantum. The photograph does not show the truncated portion of the folds because the beds are of very nearly the same texture at and near the surface of contemporaneous erosion. In the field, however, the relations are clear. The figure illustrates a section about twenty inches long.

the soft deposits, crumpling them and scraping off the crests of the folds. (3) After the disturbing agent had passed, quiet deposition continued as before.

In his visits with field classes to Squantum the writer was impressed by this peculiar phenomenon several years ago and he explained it as possibly due to floating blocks of ice. Corroborating this hypothesis is the presence of occasional isolated pebbles and

bowlders inclosed in the evenly banded slates (Fig. 1). These were thought to have been carried by the floating ice-blocks, and to have dropped as the ice melted. Mr. R. W. Sayles's study of the tillite of Squantum, cited above, is also confirmatory evidence.

The Auburndale deposits described.—Last November, at Auburndale, Massachusetts, the writer came upon a beautiful exposure of a structure exactly resembling the Squantum zones of deformation, but this time in unconsolidated deposits of a Pleistocene sand plain, (Fig. 3). The structure was seen in a sand pit. The deposit consists of fine and coarse sand and some clay, all regularly stratified with frequent variations in texture. As at Squantum, the zones are repeated at several stratigraphic levels and with no definite spacing or order. Here, then, is an example of aqueous deposition undeniably associated with glacial action. The likeness between the two cases is highly significant, particularly as regards the origin suggested.

Definition.—The relations described above are those of local unconformity associated with deformation of the upper layers of the subjacent strata. The structure is really *local angular unconformity*. Since erosion producing local unconformity is often called *contemporaneous erosion*, we may term the folding and faulting resulting from such erosion *contemporaneous deformation*.

PROBLEMS OF PETROGRAPHIC CLASSIFICATION SUGGESTED BY THE "KODURITE SERIES" OF INDIA[1]

WHITMAN CROSS
U.S. Geological Survey

INTRODUCTION

Petrographic classification has often been retarded or sent on the wrong course, for a time, by the repeated failure of petrographers, often those of deserved reputation as investigators, to observe some broad principles of systematic classification. A petrographic system which is to endure must surely be constructed with the aid of generalizations or other factors which are widely applicable to the rocks of the earth. Premature generalizations have always proved harmful when introduced into system, however helpful they may have been in their proper places, as aids in the study of particular problems. Broad system expresses general relationships of certain kinds, but many systematic propositions or criticisms are made with a desire to emphasize the peculiarities of the rocks of a locality, a district, or, at most, a province. I desire to offer a few observations on this last point apropos of a recent discussion by L. L. Fermor, and this leads to some comments on the classification of igneous rocks contained in Hatch's well-known *Textbook of Petrology*.

A recent publication by Fermor,[2] referring to both local and general problems of petrographic classification, raises a number of questions of more than passing interest. Certain manganiferous rocks of India called the "Kodurite Series" are believed by Fermor to be "a series of differentiated igneous rocks ranging in acidity from quartz-orthoclase rock, through intermediate quartz-kodurites

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] L. Leigh Fermor, "The Systematic Position of the Kodurite Series, Especially with Reference to the Quantitative Classification," *Records, Geol. Survey of India*, XLII, Pt. 3 (1912), 208–30, Calcutta.

and basic kodurites, to manganese-pyroxenites containing rhodonite and other manganese pyroxenes."[1] The kodurite proper is a rock now much decomposed, but assumed to have consisted of orthoclase, a manganiferous garnet, and apatite. Opal now takes the place of the supposed orthoclase.

What are considered to be difficulties in the way of classifying the kodurite and other highly manganiferous rocks in the Quantitative System lead Fermor to conclude that it fails in several respects when applied to such rocks or to possible ones rich in nickel, barium, strontium, or lime. On the other hand, it is said that classification of the kodurite and other rare rocks by Hatch's system is eminently satisfactory.

The evident fairness with which Fermor has essayed the classification of the kodurite rocks in the Quantitative System relieves his discussion, in most respects, from the charge of controversial tone, notwithstanding his very evident prejudice against some features of that system. The problems presented by such rocks are real ones and must be solved if manganese-rich igneous rocks occur, but there is a point of view from which the result reached by Fermor is very much more satisfactory than it seems to him, as will appear in the following discussion.

THE CHARACTER OF THE KODURITE SERIES

The rocks of the Kodurite Series were specially described by Fermor[2] some years ago. They occur in the Archean Complex of the coastal plain belt of the Madras Presidency about midway between Madras and Calcutta. In view of the importance of this series, if of igneous character, it is necessary to point out at once that this character is by no means self-evident, and that much further proof than that offered by Fermor is necessary before geologists unfamiliar with the occurrence can be expected to accept the view of their igneous origin.

The kodurite rocks occur in a lowland zone of poor exposures, the best being in the manganese mines where the secondary oxi-

[1] L. Leigh Fermor, *op. cit.*, p. 208.

[2] L. Leigh Fermor, "On the Manganese Deposits of India," *Memoirs, Geol. Survey of India*, XXXVII, Pt. 2 (1909), "Geology," 243–79, Calcutta.

dized decomposition products are exploited. They appear in association with metamorphosed sedimentary rocks of the Khondalite Series, other metamorphosed sediments, rich in garnet, called "calc gneisses," a gneissose granite, and the Charnockite Series, the last two being considered of igneous origin. Fermor points out the banded arrangement of all the rocks, the absence of contacts showing intrusive relations, and the closer association of the Kodurite Series with the metamorphics than with the igneous Charnockite Series. The only cited occurrences thought by Fermor to indicate intrusive character are in two sections, five miles apart, in which the manganese rocks occupy different relations in metamorphic zones which appear to be made up of the same elements.

The principal feature of the rocks interpreted as favoring the hypothesis of their magmatic origin is the mineral and chemical composition, which Fermor believes cannot be explained in any other way.

Before proceeding to review the characters of the rocks I wish to point out that the term "series" is commonly used in India for both metamorphic and igneous rocks as a convenient term by which to group or correlate them as an aid in the analysis of the complex and obscure Archean System. When applied to igneous masses the term has still chiefly a stratigraphic sense, is used for convenience, and is subject to free modification. "Kodurite Series" is applied by Fermor to rocks assumed to have common origin through differentiation, but this view is not as yet justified by chemical investigation or adequate knowledge of relations and the name appears to be simply a practical, justifiable term of convenience for local uses.

The Kodurite Series consists of quartz-orthoclase rock, apatite-quartz-orthoclase rock, quartz-kodurite, orthoclase rock, kodurite, pyroxene-kodurite, biotite-kodurite, spandite rock, apatite-spandite rock, pyroxene-spandite rock, manganese-pyroxenites, and graphitic manganese pyroxenites. These varieties and the intermediate phases have not been described as yet in a connected manner showing the chain of peculiar characters necessary to establish a true petrographic series. But few chemical analyses are offered by Fermor.

The series is almost unique as to its manganese minerals, if they are constituents of true igneous rocks. Garnet, manganiferous pyroxenes, and graphite are, however, common constituents of associated metamorphic rocks in India. The first and heavy burden of proof is then to demonstrate that the kodurite rocks are igneous. Known field relations do not do this, as Fermor freely admits. The lack of definite evidence to the contrary scarcely permits the acceptance of the igneous origin in view of the known occurrences of the peculiar minerals.

I am perfectly willing to admit the possibility of manganese-rich magmas as differentiation products, and even assume that they will be found; so that while not regarding the evidence adduced by Fermor as sufficient to establish the Kodurite Series as magmatic differentiates, I am quite ready to discuss the problems of classification which would be presented by such rocks.

FERMOR'S QUANTITATIVE CLASSIFICATION OF KODURITE AND GARNET ROCK

Assuming that rocks like kodurite may be of igneous origin, let us review Fermor's discussion of the problems involved in the Quantitative Classification of the Kodurite Series. That discussion is based on four hypothetical or "calculated analyses." The kodurite proper is the original rock now much altered through replacement of feldspar, believed to have been orthoclase, by opaline silica. Two of the freshest rocks were analyzed, one from Kotakarra in the Vizagapatam district, and one from Boirani in the Ganjam district. Assuming the replacement of orthoclase by opal, Fermor made an estimate of the original mineral composition of these rocks. The former is thought to have consisted of: apatite 3.36, garnet (spandite) 55.04, orthoclase 41.29, TiO_2 0.29, CuO 0.02; the latter of apatite 2.62, orthoclase 57.80, albite 2.79, garnet (grandite) 36.55, and TiO_2 0.24. From these figures equivalent chemical "analyses" have been calculated, which serve as the basis of classification of kodurite.

The two nearly pure garnet rocks, one from each of the localities above mentioned, are assumed to have the composition of the garnets in the two kodurites, as calculated from the rock analyses.[1]

[1] *Memoirs*, etc., pp. 256–61.

Table I gives the actual analyses of the Kotakarra (I) and Boirani (II) rocks; the calculated chemical composition corresponding to the estimated original mineral constitution (I*a* and II*a*); and the calculated composition of the garnets in rocks I and II, supposed to fairly represent certain garnet rocks of Kotakarra and Boirani (III and IV). In Table II the norms calculated by Fermor from I*a*, II*a*, III, and IV are also quoted.

TABLE I

ACTUAL AND CALCULATED ANALYSES

	KOTAKARRA KODURITE		BOIRANI KODURITE		KOTAKARRA GARNET-ROCK	BOIRANI GARNET-ROCK
	I	I*a*	II	II*a*	III	IV
SiO_2	54.15*	47.45	60.60†	53.36	37.57	38.18
TiO_2	0.32	0.29	0.27	0.24	.....	.....
Al_2O_3	11.50	18.00	10.59	16.31	18.98	14.22
Fe_2O_3	6.07	1.91	4.79	4.17	3.47	11.41
FeO	0.90	4.10	0.64	0.79	7.45	2.16
MnO	10.00	9.08	1.07	0.98	16.50	2.68
MgO	0.14	0.13	0.26	0.22	0.23	0.65
CaO	11.67	10.37	13.87	12.54	15.80	30.70
K_2O	0.01	6.97	4.00	9.75	.....	.....
Na_2O	0.18	.....	0.36	0.33	.....	.....
P_2O_5	1.60	1.42	1.24	1.11	.....	.....
CaF_2	.....	0.26††	.....	0.20††	.....	.....
CuO	0.02	0.02	trace	.....	.....	.....
H_2O 100°+	1.33	.....	1.20	.....	.....	.....
H_2O 100°	2.30	.....	1.30	.....	.....	.....
Total	100.19	100.00	100.19	100.00	100.00	100.00

* Combined SiO_2 = 35.50: free SiO_2 = 18.65.
† Combined SiO_2 = 32.25: free SiO_2 = 28.35.
†† Calculated from fluorine assumed in apatite.

A rock having the composition of I*a* would be, as Fermor has shown, a perpotassic andase in the Quantitative System (II. 5. 3. 1); one like II*a* would be a perpotassic monzonase (II. 5. 2. 1). No perpotassic rock of either of these rangs has been described previously and Fermor proposes the names kodurose and boiranose, which cannot be accepted, as shown below.

The further quantitative classification of I*a* on the basis of the amount and chemical character of the femic constituents is carried out by Fermor in accord with the principles of the system.

Manganese is recognized by calculating its ratio to ferrous iron and establishing subsections of subgrad, one step farther than has been necessary hitherto.[1] Fermor also calculates the position of II*a* to the subsection of subgrad, but the small amounts of magnesia, ferrous iron, and manganese (together but 1.99 per cent) make it quite unnecessary to go beyond the precalcic subgrad. The hypothetical garnet rocks, III and IV, fall in the Salfemanes, and their classification is also calculated by Fermor to subsections of subgrad.

TABLE II

NORMS FROM CALCULATED ANALYSES

	KOTAKARRA KODURITE	BOIRANI KODURITE	KOTAKARRA GARNET-ROCK	BOIRANI GARNET-ROCK
	Ia	IIa	III	IV
Orthoclase	35.47	55.60	.....	.....
Leucite	4.53	1.61	.....	.....
Nephelite	.....	1.50	.....	.....
Anorthite	28.44	14.15	51.74	38.75
Diopside	.....	1.19	.....	3.50
Hedenbergite	11.02	.....	7.25	.....
Wollastonite	0.93	16.71	.....	5.49
Akermanite	.....	.....	6.71	34.87
Fayalite	.....	.....	5.80	.....
Tephroite	12.93	1.39	23.47	3.80
Magnetite	2.76	1.86	5.03	6.96
Hematite	.....	2.89	.....	6.61
Ilmenite	0.55	0.46	.....	.....
Apatite	3.33	2.62	.....	.....
	99.96	99.98	100.00	99.98

The procedure by which Fermor provides a place for manganese-rich rocks in the Quantitative Classification is, as just noted, quite in harmony with the principles of the system, and on that score its authors have no criticism to make. But in regard to the various names proposed by Fermor, we must point out, in response to his request, that all of them are quite unwarranted and cannot be accepted since they are based on "calculated analyses" derived

[1] See Cross, Iddings, Pirsson, and Washington, "Modifications of the Quantitative System," etc., *Jour. Geol.*, XXII (1912), 552–53.

from analyses of much-altered rocks.[1] With increasing experience it becomes more and more clear that quantitative system names should be based only on good analyses of fresh or but slightly altered rocks. Fermor's "calculated analyses" are clearly liable to errors unfitting them for any systematic use, however valuable and justifiable they may be in discussing the nature of the alteration that has taken place. Kodurite of both types and the garnet rocks are, like many of their associates, very interesting and unusual types and, if their igneous character can be established and good analyses furnished, some of them will undoubtedly fall in divisions of the Quantitative System in which there are at present no other known representatives, and new quantitative names may well be based on them.

Fermor is not satisfied with the result of applying the Quantitative System to the four hypothetical rocks, and points out what he regards as the defects of the system indicated by this case. He considers it a serious flaw in the system that the subrang is reached without reference to the important constituent normative tephroite (12.93 per cent in I*a*) and further that rocks poor in manganese may fall in the same subrang. This criticism touches the fundamental distinction between salic and femic components which it seems unnecessary to discuss at this time. Other criticisms may best be expressed in the following quotations:

> There certainly seems to be something lacking in a system which takes no effective account, until the ninth subdivision of the system is reached, of a constituent that is fourth in order of importance in the chemical analysis and third in order of importance in the norm.
>
> The same criticisms apply to boiranose, but to a much smaller degree on account of the much smaller amount of MnO present; but they apply in an even more striking manner to the Kotakarra garnet-rock (spandite-rock), in which MnO is third in order of importance in the chemical analysis, and tephroite, Mn_2SiO_4, is second in order of importance in the norm, of which it forms nearly 25 per cent.[2]

[1] Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks*, p. 166. This and all other references to the Quantitative System contained in this paper are made with full approval of my colleagues. A review of all names proposed since the Quantitative System was first published will be given by Dr. Washington in a forthcoming new edition of his *Chemical Analyses of Igneous Rocks*.

[2] *Records*, p. 217.

The natural reply to all such criticisms is mainly a reference to certain principles which must be recognized in any systematic classification of igneous rocks. Fermor clearly desires a method of classification specially adapted to the peculiar "Kodurite Series," the rocks he happens to be working with. But a local or provincial "series" is not and cannot be made a broad systematic concept. Such a series has certain features or characters common to other series, but that which specially characterizes a local series is surely not a factor to be prominently introduced into systematic classification of rocks in general. Any comprehensive system must recognize first the factors which are important because common to, though variable in, many rocks, and later take up those which are notable in addition as distinguishing a few.

General petrographic system must bring out through classification the relations of kodurite to other rocks, as well as its peculiarities. The hypothetical kodurite has other notable chemical characters besides its manganese contents. It is assumed to be remarkably rich in potash and poor in soda; rich in lime and poor in magnesia. It is these characters that show the relation of such a type to other rocks, not the unique richness in manganese. To express these broader relations is the object of systematic classification, and it is these factors of general chemical relationship which are logically applied in the Quantitative System.

An igneous rock having the composition assumed for kodurite would be a new and interesting magmatic variety irrespective of its manganese, through its quite abnormal association of high lime and potash with low magnesia and soda. The Boirani kodurite possibly falls in another perpotassic subrang, of higher lime contents even in its salic molecules, and still more markedly calcic in its femic constituents, than kodurite proper. These facts are just what a logical system should bring out before the unusual richness in manganese finds expression. No system can be constructed permitting the application of each of the many chemical elements of igneous rocks in accordance with its order of prominence in each case, now first, now fifth, now tenth.

From this point of view the fact that the unusual richness of the Kotakarra kodurite in manganese finds expression in the

eighth place in the Quantitative System seems quite appropriate. It is certainly plain that a scheme recognizing manganese in the third place would, for example, not serve to bring out the actual close relationship which exists between the Boirani and Kotakarra kodurites, for the former has only 0.98 per cent MnO. Fermor himself points out that, considering manganese as the characteristic thing about kodurite, the Boirani rock is classed with it simply for convenience. It is modal garnet and orthoclase or normative anorthite and orthoclase which bring the rocks together.

Fermor expresses the opinion that the Quantitative System does not possess either the elasticity or the comprehensiveness which the writer has said should be found in a satisfactory classification. If by elasticity is meant the possibility of transposing certain fundamental parts of the structure at will, according to the varying prominence of certain constituents in different rocks, the first part of this comment is true, but it may be answered that no real *system* can be so constructed. The section of subgrad necessary to express the manganiferous character of kodurite is, however, not an *appendix*, as Fermor considers it. It is an extreme division of the system connected appropriately with the rest in a manner provided for in the original publication.

"Kodurose," as a subgrad magmatic name, does not itself express all the chemical relations involved, but it is no more necessary to go over all the steps of the classification by which this division has been reached, whenever it is referred to, than it is in using the specific or varietal names of animals or plants. It may be pointed out that where the chemical relations of igneous rocks are in question, the new symbols for expressing quantitative classification do show the whole systematic position far better than does any existing scheme for concise statement in zoölogy or botany.[1] "Kodurose" does express the important relationships of such a manganese rock to other rocks in all important respects—when the system is understood.

Fermor considers the Quantitative System unable to deal with rocks containing large amounts of oxides of manganese, nickel,

[1] Cross, Iddings, Pirsson, and Washington, "Modifications of the Quantitative Classification," etc., *Jour. Geol.*, XX (1912), 553–57.

barium, strontium, etc., because the system, as published, does not contain all the detail applicable to such cases. He cites, however, the remark by the authors of the system that the above-named oxides are to be grouped with FeO or CaO "unless these unusual components occur in sufficient amounts to make their calculation as special mineral molecules desirable." It was believed by the authors that the principles and methods of the system were so clearly illustrated by the scheme published that petrographers would understand the extension of the framework of the system to rocks in which any rare elements might acquire local prominence. Fermor's treatment of the manganese rocks is in accord with that assumption.

With regard to *sections* it was remarked:

> The application of the above principles [used in the construction of the system] shows, however, that in certain points more numerous subdivisions are needed. This necessity is met by the formation of *sections* of any of the divisions above described. These sections will be based on more special characters according to circumstances.[1]

It is of course possible that igneous rocks may sometime be found containing in notable amounts rare substances which must be introduced into the norm, and where the exact method of procedure in systematic treatment may not be plain. But even in the case of barite, raised by Fermor, its position in the group A of femic molecules is appreciated by him and the recognition of the various molecules of this group in the system, while somewhat complicated, will not prove very difficult. Until the occurrence of barite as an original constituent of igneous rocks is conclusively demonstrated it seems unnecessary to work out the details of its treatment in the Quantitative System. The igneous nature of the quartz-barite rock of Salem, India, mentioned by Fermor, can hardly be considered as proven, at the present time. The new divisions of the Quantitative System which may be made necessary for rocks of unusual chemical composition will not be appendices of the system, in the sense of unrelated appendages.

[1] *Op. cit.*, p. 127.

CLASSIFICATION OF KODURITE SERIES BY HATCH'S SYSTEM

While Fermor considers the Quantitative Classification of the Kodurite Series unsatisfactory, as illustrated by the four hypothetical rocks specially discussed, he states that he is able to classify the whole series with ease and accuracy in the modified form of the mineralogical system recently proposed by F. H. Hatch,[1] and draws the attention of the American petrographers to the "elasticity of Hatch's classification."[2] Believing the kodurite rocks plutonic, Fermor adds "a mangan-subseries of the potash series" and introduces the Kodurite Series intact, with its new names, in Hatch's system. Whether Hatch considers this claim for the elasticity of his system correct or not I do not know, but I do not understand that *any* existing system permits the introduction of local or provincial series as such in its framework.

The discussion of Fermor's procedure in applying Hatch's system to the Kodurite Series may well be left to the author of that system, but, as one who has studied the subject of systematic classification of rocks from many standpoints, I wish to make the comment that the principles of general system and the considerations that control in the expression of provincial characteristics in a so-called "rock series" are almost antithetical. A scheme containing three or four such series intact would cease to be a system. The term "series" is applied by Hatch and Fermor to very different concepts.

It would seem to me that the case of the Kodurite Series was directly covered by the following statement of Hatch:

> Although names founded on mineralogical variation in constituents other than the feldspars are of little service in classifying rock-types, they are often useful for descriptive purposes. They form no part, however, of the system of classification now undergoing discussion.[3]

HATCH'S PETROGRAPHIC SYSTEM

The classification of igneous rocks presented by Hatch in the fifth edition of his *Textbook of Petrology* (1909), and repeated in

[1] F. H. Hatch, "The Classification of the Plutonic Rocks," *Science Progress*, October, 1908; *Textbook of Petrology*, 5th ed., 1909; 6th ed., 1910; 7th ed., 1914.

[2] *Records*, p. 225. [3] *Science Progress*, p. 7.

later editions, is very nearly the same, in effect, as other forms of the mineralogical system which have been in use for many years past. But he introduces certain new factors, intended to give the system greater precision and a quantitative character hitherto wanting. Because of the frankly expressed object of the author to formulate a classification free from the, to him, objectionable features of the Quantitative System, it seems appropriate to review some features of the revised system. I wish to emphasize the fact, however, that the critical comments to be made are, almost without exception, of general application to many earlier propositions and are not personal to Hatch.

The attitude of Hatch toward the Quantitative System and the claims made for his own scheme are in part expressed in the following quotations:

> In the quantitative classification of igneous rocks devised by Messrs. Whitman Cross, Iddings, Pirsson, and H. S. Washington, the hitherto existing nomenclature of rock types is entirely discarded, and a new nomenclature introduced which is based on purely chemical considerations without regard to mode of origin. . . . .
>
> I desire in this paper to show that it is not necessary to throw over the existing rock nomenclature, nor to *disregard mode of origin, in basing a natural system of classification on chemical considerations.*[1]

The element in Hatch's system which underlies the claim that it is a "natural system" is the primary division by "mode of occurrence" into plutonic, hypabyssal, and volcanic rocks. Mode of occurrence is, indeed, a criterion for the classification of igneous rock masses, and Hatch devotes a chapter to this subject. Where this primary division is made, Hatch points out that "volcanic-rocks are, however, connected with their deep-seated or plutonic roots by necks and pipes, or by dikes. A third division of igneous rocks is therefore necessary to embrace these connecting links between plutonic and volcanic rocks. For this division the term *hypabyssal* is used."[2]

But neither Hatch nor any other systematist using plutonic in this sense necessarily means deep-seated or abyssal. He means granular, and yet it is known that certain granular rocks, treated

[1] *Science Progress*, p. 1. Italics by W. C.

[2] *Textbook of Petrology*, 5th ed., pp. 7 and 8; 7th ed., pp. 5 and 6.

as plutonic, occur side by side with rocks termed hypabyssal, and some have been formed near if not at the surface. In treating the hypabyssal rocks, Hatch shows that he is largely influenced by Brögger's proposition to apply this term to the "Dike rocks" of Rosenbusch. The complex genetic, structural, and textural relations involved in this conception are well known and need not be stated here. And in view of an earlier discussion of this subject[1] I need only repeat that the use of these natural relations of rocks in classification must be appropriate and consistent with the facts, or the result is *unnatural*.

The expression "natural system" as applied to petrographic classifications should, I think, refer to other things as well as to the use of factors of natural occurrence. The rocks themselves have various *natural* characters or properties. The systematist makes use of these characters in classification and should do so as appropriately and consistently as possible. In proportion as the nature of rocks is rationally applied in their classification the result may be termed a natural system. It is with reference to this idea that the further systematic propositions adopted by Hatch will be considered. They are, for the most part, not new.

The next step is the distinction between feldspathic and non-feldspathic rocks. The two groups of substances indicated by this division occur in rocks in all amounts from 0 per cent to 100 per cent for each. If this varying constitution of two exclusive groups of minerals is to be used as a systematic factor in classification, is it not the natural way to recognize the varying proportions of the two groups? To call all rocks distinctively *feldspathic* which contain as much as 10 per cent of feldspar is to ignore the fact that rocks with 10 per cent or more of pyroxene are by the same measure *pyroxenic*. In short, this is a quite unnecessarily arbitrary and unnatural procedure and opposed to the almost universal tendency of modern petrographers to introduce a quantitative element into system wherever it is appropriate and feasible.

It is to be presumed that "chemical considerations" lead Hatch to form three groups of rocks called *acid*, *intermediate*, and *basic*,

[1] Whitman Cross, "Natural Classification of Igneous Rocks," *Quar. Jour. Geol. Soc.*, LXVI (1910), 470–506.

marked off by the percentages of silica shown on analysis, the lines being drawn at 66 and 52 per cent. These limiting percentages are admitted by Hatch to be "quite arbitrary" but permitting "a convenient separation in accordance with existing records of rock types."[1] The meaning of the latter phrase is not clear to me. Now it must be self-evident that no *chemical* consideration of importance, to say nothing of a principle, requires or suggests a division of igneous rocks by any special silica percentages whatever. Calling the group with more than 66 per cent SiO_2 "acid," and designating all the rocks of this group as the "Granite Family," implies that only rocks of this silica content may contain important amounts of quartz. The application of the name "Syenite Family" to alkalic rocks of the intermediate group implies that they must be quartz-free, or nearly so. And the designation of the group with less than 52 per cent SiO_2 as "basic" implies the generalization that quartz is absent and that silicates of such rocks must be less rich in silica than those of the intermediate group.

The well-known facts are that many rocks having less than 52 per cent SiO_2 contain metasilicates and several per cent of free silica; many intermediate rocks carry 25 to 30 per cent of quartz; and many of 66 per cent carry little or no quartz. It is a fundamental principle, ignored by Hatch, that the petrographic importance of the silica contents of a rock, as influencing the development of its minerals on crystallization, can be determined only by a study of the relative amounts of the associated bases and recognition of their influence in the magmatic solution. This principle is illustrated by the normative calculations on which the Quantitative System is based.

The fact that the silicity[2] represented by 66 per cent SiO_2 has no relation to the presence of free quartz is illustrated by three analyses quoted by Hatch in tables representing the Calc-Alkali Series.[3] In Washington's tables it is shown that the granodiorite of SiO_2 68.65 has 24.2 per cent normative quartz; the tonalite of

[1] *Science Progress*, p. 2.

[2] A useful term of self-evident meaning recently proposed by Washington (this *Journal*, XXII [1914], 16).

[3] *Science Progress*, p. 9.

SiO_2 63.09 has 22.9 per cent normative quartz; the quartz diorite of SiO_2 57.41 has 11.5 per cent normative quartz. Many rocks are nearly normative in their quartz contents and some carry more than the normative amount.

The ultrabasic rocks furnish further evidence, if such is necessary, that a division of rocks by silica percentage is without reason and without object so far as any relation between chemical and mineral composition is concerned. The line of 52 per cent silica, established by Hatch between intermediate and basic rocks, is passed by the silica of some rocks placed by him in the *ultrabasic* group, e.g., websterite, one analysis of which, cited by him, has 53.25 per cent SiO_2.

The norms of many of Hatch's ultrabasic rocks contain 20 per cent or more of feldspar and lenad. And while such amounts are not common in the *mode* of the plutonic rocks in question, those of the surface or hypabyssal forms of equivalent chemical composition are often notably feldspathic. This well-known variation in mineral composition, due to physical conditions, must be considered in any adequate systematic treatment of the more basic or "ultrabasic" rocks.

After the arbitrary division on silica percentage, Hatch introduces the character of the feldspars and feldspathoids as the factor for the next subdivision. It is his evident intent to emphasize the quantitative element in many places, but this is often by use of the vague terms "predominant," "largely developed," and "subordinate." The meaning attached to such terms is often highly subjective, as appears most striking in the case of the "Feldspathoid Series," which is defined as one "in which nepheline, sodalite, or allied feldspathoid is largely developed, and feldspar subordinate."[1] But Hatch cites, as illustrating the "Feldspathoid Series," the average of nine typical nepheline syenites, given by Brögger, and the norm calculated from this, which must approximate closely to the mode, gives feldspars 69.11 per cent, and nephelite 20.3 per cent. That is, the feldspars, which must be more than three times as abundant as nephelite in a rock of the cited composition, are declared "subordinate," and the nephelite

[1] *Science Progress*, p. 3.

relatively "largely developed." Many phonolites, foyaites, and nephelite syenites carry but 10 per cent or even less of feldspathoid. There is no indication of the minimum amount of nephelite or leucite which Hatch would consider as placing a rock in the "Feldspathoid Series."

In subdividing the feldspathic rocks still farther, Hatch introduces as a direct quantitative factor the relative percentages of alkali feldspars as against plagioclase, and of soda as contrasted with potash feldspar. This is certainly a step in the right direction, but as it comes after the irrational silica distinction, it loses much of the value it might have in bringing allied rocks together.

It is to be hoped that Fermor will succeed in establishing the origin and chemical character of the interesting rocks called the Kodurite Series. If they possess the characters assumed for them, it appears to me that the Quantitative System will show—so far as it professes to go, that is, in expressing chemical characters—both their general chemical relations to other rocks and their unique special features.

The use of factors of natural occurrence in the classification of igneous rocks does not necessarily make the system natural. The system of Hatch, like many others of allied construction, does not seem to me to use natural factors in a rational way And as actual characters of the rocks are used with unnecessary arbitrariness the right of his and allied systems to be termed natural is open to question.

The systematic treatment of igneous rocks, with all their widely varying important characters, is a matter of great difficulty, and a long time may elapse before petrographers come to a common point of view. It is in the hope of contributing, however slightly, to this understanding, that this discussion has been written.

A PHENOMENON OF THE KANSAN DRIFT IN NEBRASKA

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Among the minor phenomena of the glacial drift in Nebraska there is one which, though rarely observed by the public, is of interest and should be commended to the attention of naturalists. The reference here is to certain large, well-defined masses or blocks of such materials as sand, gravel, and coarse pebbles, which occur imbedded in the drift clays along with glacial bowlders, and which presumably have been similarly transported and deposited. These masses or blocks vary widely in color, texture, and kind. They also vary from the glacial matrix in which they are found and are the more striking by virtue of contrast. They are not of frequent occurrence, but may occasionally be seen in fresh exposures especially in deep railroad cuts. Unfortunately they are quickly effaced by weathering and by growing vegetation. The most notable examples are found in the Milford cut-off of the Burlington Railroad, particularly at Pleasantdale. For a mile or so west of the station at Pleasantdale, especially on the right bank, fine examples occur in almost continuous succession (see the accompanying sketch and photograph).

The drift at this place is a jointed sandy clay of a rusty gray color, of a fairly compact texture, and about twenty-five feet in thickness. It is somewhat startling to find in it great stray blocks of various materials. These blocks are generally large and angular or rounded masses of incoherent soil, sand, and gravel, more or less stratified, cross-bedded, and tipped at all angles. It is still more surprising to find sections of small stream beds and channel deposits tilted and overturned. The dense quartzitic and occasional granitic bowlders characteristic of the Nebraska drift, and these incoherent sand and gravel blocks occur together. Perhaps the arenaceous and argillaceous blocks were likewise dense and coherent at the time of transportation and

deposition, the assumption being that they were rigid because frigid. Accordingly we have coined for them, and for a long time

FIG. 1, *A*.—A bank of Kansan drift at Pleasantdale, Nebraska, showing "frigites" of clay, sand, gravel, and pebbles (see *B*). Distance to bridge about 1,000 feet.

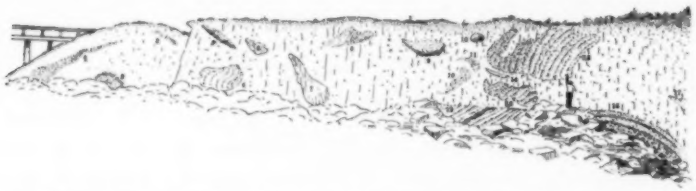


FIG. 1, *B*.—Key to *A*. Nos. 1, 3, 4, 8, 10, 11, 13, 14, 17 represent sand blocks ("sandfrigites"). No. 12 is a large cross-bedded sandfrigite about 30 feet long partly buried by talus. No. 15 is a large very distinct sandfrigite about 30 feet long. Nos. 2, 5, 9, 16 are supposed stream beds ("couleefrigites"). Nos. 6 and 7 are clay blocks ("clayfrigites"). No. 18 is a large Sioux quartzite bowlder. Total length of section about 1,000 feet.

have used as a convenient generic field name, the word "frigites," and have used as specific terms the additional names "soilfrigites," "clayfrigites," "sandfrigites," "gravelfrigites," "couleefrigites,"

etc., according to the component materials. Perhaps, as has been suggested, these are Aftonian.

Incident to the protracted frigidity of a glacial period is the freezing of soils, sands, and gravel to the rigidity of rock (frigite). Any natural force which could rend and transport rock could rend and transport the rocklike soils and sands. Continental glaciers are powerful graders and levelers. They act resistlessly upon rock and frozen soils and sands, breaking them into blocks and transporting them long distances southward. The load of rocks and frozen blocks is finally dropped by the melting ice, and buried in glacial mud. The blocks are thus preserved in their integrity. A stream bed, or coulee, could in a like manner be frozen, subsequently broken into sections, transported, and deposited.

The term "glacial drift" as used in an unfortunately restricted and local sense in Nebraska refers to that particular portion of the Kansan drift, which is rendered conspicuous by coarse pebbles and bowlders of reddish Sioux quartzite. This layer is pretty generally recognized, and though it may be but a foot or two in thickness it is often expedient to speak of it popularly as "the drift." In a broader sense, however, our drift also includes, though less obviously, extensive beds of glacial clay, generally spoken of as joint clay, which may reach fifty feet in thickness. It has long been said facetiously by eastern geologists that the glacial deposits of Nebraska are "buttered on so thin that one cannot tell the buttered side." It is probable, however, that this bit of good humor would never have become classic had our drift not been confounded with our loess. There may be recognized an older, bottom layer of a dark, or even black color (sub-Aftonian, Jerseyan, or Nebraskan), and a younger, top layer of a lighter color, generally of a yellowish or reddish cast (Kansan), neglecting any Aftonian sands and gravels. The frigites herein described are confined to the Kansan drift.

It so happens that the drift often resembles the loess so closely that they run together, and seem to be terms in the same series. At times it puzzles even those who are experienced to distinguish between them. The southeastern half of Nebraska has for convenience been generally figured as one continuous loess sheet.

It must be noted here that there are extensive "loessless" regions in the southeastern as well as in the northeastern corners and elsewhere in the state. Frozen sand blocks have been observed in the drift of Iowa as well as in Nebraska, but as far as can be learned no examples yet found equal those in the Milford cut-off in point of size, variety, or numbers.

EDUARD SUESS

WILLIAM HERBERT HOBBS

Of men, as of mountains, it is often true that one towers in isolated grandeur well above his fellows. Of the lower eminences there arise questions of relative prominence, but of the one, never. Eduard Suess, who passed from life on April 26, ranked as one of the intellectual giants of his age, and his masterpiece, *Das Antlitz der Erde*, as the greatest work upon geology since the modern science was founded three-quarters of a century ago in *The Principles of Geology* of Sir Charles Lyell. Already past eighty, Suess had for years been fighting the encroachments of advancing age in a hardening of the arteries, and his death following upon a bronchial affection came peacefully at his home in the Afrikanergasse, Vienna. His friends in every land, and they were many and devoted, will in mourning his loss not fail to account it a special mercy that he was spared a knowledge of the world cataclysm, in the storm center of which his country is now struggling under severe reverses, and which its harsh demands upon Servia precipitated. Deeply interested as he was in the political life of his country, and high as he ranked in its councils, the predicament in which Austria-Hungary now finds herself, with the consciousness of responsibility for it, must have rested with especial weight upon him. Passing away when he did, his last years were happy ones, as unsought honors and evidences of devotion and esteem multiplied, with his life work gloriously completed and his son succeeding to his own chair at the University of Vienna.

Professor Suess was born in London, August 20, 1831, where his Saxon father was an importer of Bohemian wool, but while Eduard was still young the family removed to Prague in Bohemia and later to Vienna. England he often referred to as his "native land," and he retained a lively interest in English affairs. Though intended for a commerical career, Suess attended the universities

of Prague and Vienna, where his field of specialization was paleontology. In the Austrian capital, his home since 1845, he was in 1852 made an assistant in the geological department of the Hofmuseum and carried out important studies on graptolites and brachiopods. Five years later he was made *ausserordentlicher Professor* in the university while still retaining his position in the Hofmuseum. Later this museum work had to be given up because of increasing duties in the university, and in 1867 he was made *ordentlicher Professor*, or full professor, of geology. After occupying this chair for thirty-four years, he delivered his farewell address July 13, 1901, as much revered as a teacher as he was distinguished as scholar and seer. Among his students he numbered such eminent geologists as Neumayr, Mojsisovics, Fuchs, Waagen, Penck, and the venerable Judd, who has so delightfully described the relations which existed between the master and his disciples. He tells us: "Amid all the fun and frolic, the signs of affectionate respect and devotion to the great teacher were never for a moment wanting." The generations of students which assembled for the farewell lecture in Vienna ranged "from the renowned and gray-haired members of the Royal Academy to the young fellows with sharp eyes." Looking out over this remarkable assembly, Suess thus concluded his address:

> Bulwer Lytton says in his novel: "When a man of great age is surrounded by children, he then sees at the end of his days, not a period, but a comma." This applies in equal measure to the inquirer and his students. This is my good fortune which today becomes my portion. . . . .
>
> And now I have reached the comma. When I became teacher, I did not cease to be a student; and now that I cease to be a teacher, I shall not cease to be a student so long as my eyes see, my ears hear, and my hands can grasp. With this wish, I therefore do not step out, but take up my former position.
>
> And now I thank you all from the depths of my heart for your presence, and beg of you to retain for me a friendly remembrance.

From this discourse, which fortunately has been published in English translation,[1] one is tempted to quote at length, since it reveals the springs of Suess's powerful influence over all who came

[1] Charles Schuchert, "Farewell Lecture by Professor Eduard Suess on Resigning His Professorship," *Jour. Geol.*, XII (1904), 264–75.

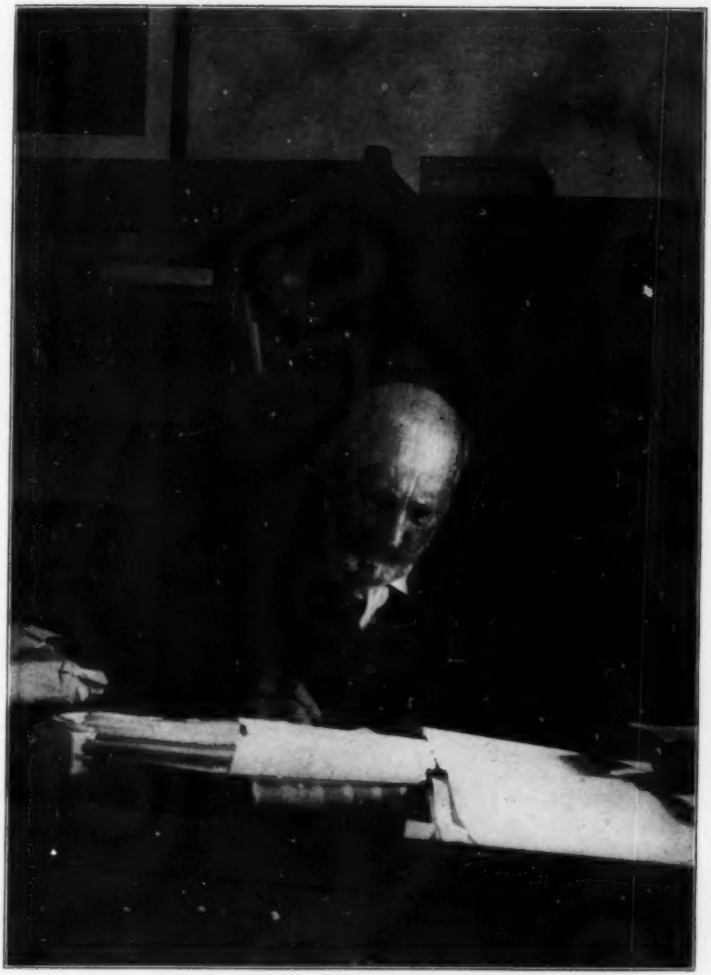
EDUARD SUESS

in touch with him. To know him was to love him for his many noble traits of mind and heart.

The great success of the *Antlitz der Erde*, the four massive volumes of which have been translated into both French and English,[1] is to be ascribed to a wonderful command of the entire field, due to a knowledge of many languages, to the accessibility and assiduous use of vast storehouses of geological literature, and to a quite remarkable grasp upon this full material with a power to generalize. Walking through the library of the Hofmuseum and passing the *Diener*, or servant assistant, whose duty it had been for twenty years to carry books from the library to his study, Professor Suess remarked to the writer: "When the *Antlitz* had appeared the *Diener* showed amazement that it was not larger, and said to me, 'Is that all you got out of the books I brought you?'"

The honest critic must frankly admit that, great as is this masterpiece of geological generalization, it suffers from two rather serious defects. Its author was almost too clever as advocate and parliamentarian and was, moreover, not without bias. With a manner altogether masterful, he could dismiss as it were with a wave of the hand important evidence which was unfavorable to maintenance of his thesis and, with equal ability, could magnify the weight of much less valuable or unimportant observations. Again, his great work suffers from a bewildering detail and an enumeration of localities too small to appear upon maps outside the original articles but upon which the conclusions are absolutely dependent, so that the reader is prevented from following the author's argument. This latter defect Professor Suess fully realized and he would have welcomed the preparation of a special atlas which should supplement his work. To offset this serious defect in overabundance of detail, which tended to make his volumes dry and difficult to read, they were written in a style so full of imagery and of poetic feeling as to hold the reader and compel his admiration. By Sir Archibald Geikie the *Antlitz* has been termed "a noble philosophic poem in which the story of the continents and the oceans is told by a seer gifted with rare power of insight into the past."

[1] Vol. I is translated into Italian.



PROFESSOR SUESS IN HIS STUDY

(From an unpublished photograph taken by his granddaughter, Fräulein Hedwig Neumayr.)

After first treating of the continents, Professor Suess at the opening of his second volume thus turns his attention to the oceans:

We have descended from the high mountain country and taken our station at the borders of the sea. The eye roams untrammeled over the vast expanse of water. A great wave approaches; it seems about to reach us; then its crest curls forward, it plunges downward, and with a dull roar the watery flood sweeps far up toward us though without wetting our feet. Now the water streams back and a long green line of sea-weed marks the limit of its advance. Then follows a second and soon a third wave, and from time to time one somewhat higher than the others which whirls the sea-weed still farther up the beach and drives us back to the foot of the cliff.

The roll of the water is repeated like the refrain of a mighty anthem. For hours we could be held captive by the sublimity of the spectacle. But now the crest of the wave is breaking at a greater distance from us, and soon the lowest position of the ebb will be reached. Then the ocean rises and all the abandoned streaks of white mussel shells and the green coils of sea-weed are gathered up again as the foot of the wave advances farther and farther. When six hours have elapsed the point is again reached where we first took up our position, and once more the water laps at the foot of the cliff.

Thus to a stately measure the heavenly bodies move the swaying ocean and bring about its advance and retreat upon the strand.[1]

One other selection may be chosen to afford some idea of the force and beauty of Professor Suess's literary style:

It is the twentieth of June of the year 1320. The bells are ringing in the bright Sabbath morning and the crowd is saluting with respect a tall and serious figure—the great Dante—who with slightly bowed head is entering the chapel of Santa Helena.

All that can stir the human soul he has felt, and in the realm of the imagination he has traveled greater distances than any mortal before him. The loss of his Beatrice he has survived, and that of his emperor from whom he had awaited a better future for his Fatherland. Now fleeing from the hatred of his own city he has found refuge at the court of the leaders of the North Italian Ghibellines. . . . . With a gift for picture-writing never before equaled he has led his astounded contemporaries up to the abode of the saints and down into the depths of the lower world. Now today he is returning to the starting-point of his most powerful creation, to the critical examination of that which is greater than all the conceptions of poetry—the actual ordering of the universe.

Professor Suess's activity in the political life of Vienna has been somewhat overshadowed by his distinction as a scholar, but

[1] Author's translation.

he gave freely of his time and his wise counsel both to municipal and national affairs. For ten years he was a member of the Municipal Council of Vienna, and for more than thirty of the Austrian Parliament as the strong exponent of progressive principles and the determined foe of special privilege. His part in the *Kulturkampf* as an anti-clerical made for him many powerful enemies, and this oppositon was reflected in the bitter attacks upon his scientific conclusions in the period before he had achieved world renown. An attribute of greatness was his simple and modest demeanor. Empty honors he scorned, and, unlike so many of his Teutonic colleagues, he declined the high-sounding state titles and remained plain "Professor Suess" to the day of his death. He seemed to take pleasure, however, in the position of President of the Royal Imperial Academy of Sciences, to which with proper pride his scientific colleagues again and again re-elected him; and he did not decline the many memberships in foreign scientific societies which indicated the high approbation of the scientific world. In recognition of his suggestion and carrying to completion of a plan to bring the pure waters of the Alps to Vienna, his fellow citizens conferred upon him their highest honor by making him an Honorary Burgess of the city.

The practical nature of some of his other studies is indicated by his monographs on "The Future of Gold" and "The Future of Silver," widely known and read throughout the world.

Reviews

The Ostoleogy of the Chalicotheroidea. By W. J. Holland and O. A. Peterson. Memoirs of the Carnegie Museum, Vol. III, No. 2, 1914.

No contribution to paleontologic science made by the Carnegie Museum of Pittsburgh presents more material of interest than the recent work on the chalicotheres by Dr. Holland and Mr. Peterson. Though representatives of this peculiar group have been certainly known in America for many years, beginning with the first recognition of remains from the Tertiary of the West by Marsh in 1877, these animals have been among the most imperfectly understood of the American Tertiary mammals.

The marvelous discoveries of Miocene mammals at the Agate Spring quarries in the past few years have fortunately included most excellent material of the chalicotherian genus *Moropus*. With the material obtained by the Carnegie Museum as a basis for comparative study, Dr. Holland and Mr. Peterson have in a most commendable manner taken up the description of the osteology and the affinities of the Chalicotheroidea of America. The present monograph is a very satisfactory description, illustrated with excellent figures representing the osteology of these forms, and bringing into view through comparative study all of the American material.

The paper combines a statement of detailed description and analysis of the skeleton with the generalizations required in reconstruction of the animal, and in the statement of affinities of the genera.

Workers in the field of paleontology and geology are certainly grateful to the authors for bringing together all of the available information on this group, and for giving us this excellent discussion of the osteology and relationships. This paper also furnishes material which makes it possible to determine, compare, and correlate fragmentary chalicotherian material from many widely scattered Tertiary deposits through the West, and to obtain from the study of these fragments more satisfactory conclusions as to the faunal relationships of the beds concerned than have heretofore been secured.

John C. Merriam

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